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X-Ray Digital Radiography and Computed Tomography of High Energy Density Physics (HEDP) Material, Subassemblies and Targets

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July 19, 2006

Disclaimer

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Presented by:

William D. Brown
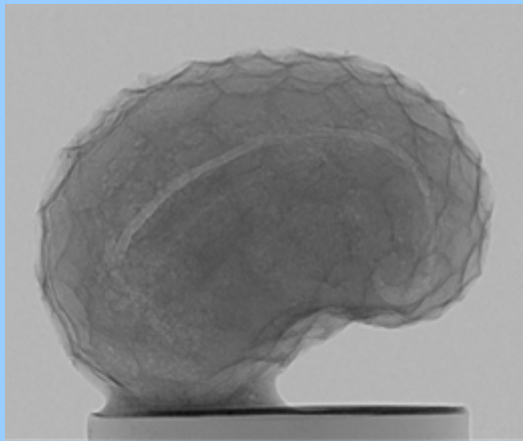
Lawrence Livermore National Laboratory

Collaborator:

Harry Martz

UCRL-PRES-

DR image (I/I₀)
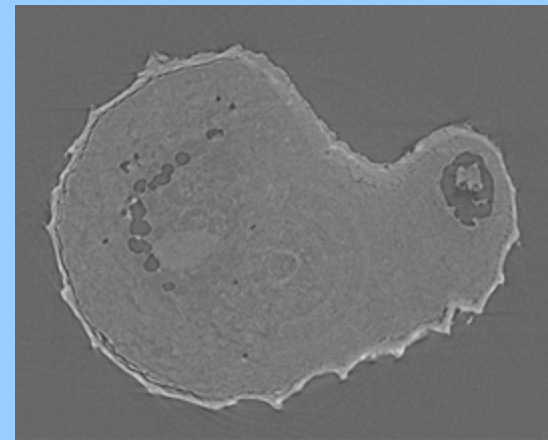
CT image (x-y plane)

ASNT Digital Imaging IX Topical Conference
Mashantucket, CT
July 24, 2006

UCRL-PRES-#

Presentation outline
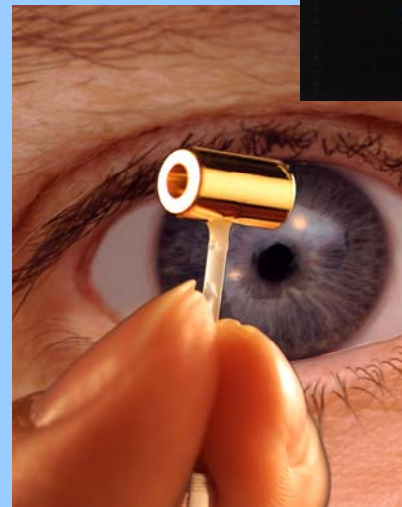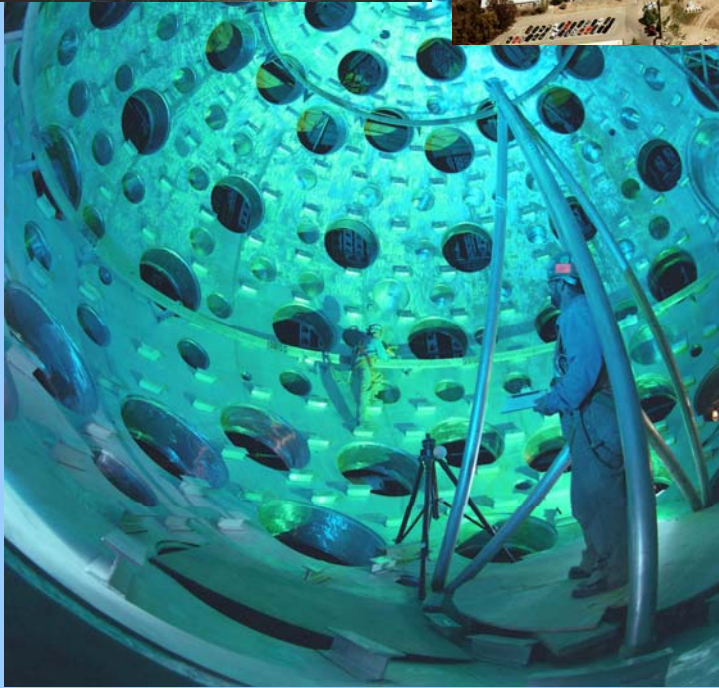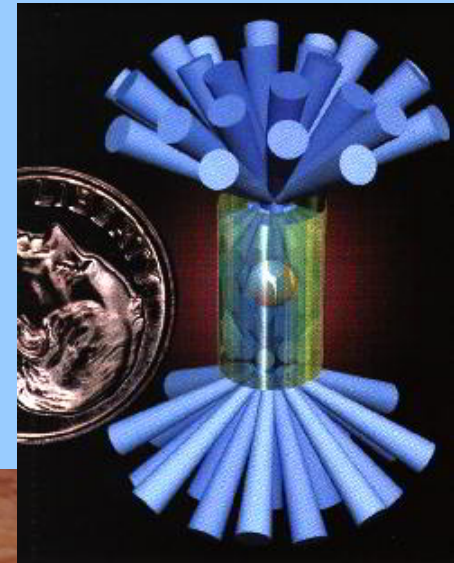
- **LLNL DR/CT mesoscale systems**

- **X-ray DR system performance**
  - **MTF**
  - **SNR**

- **Mesoscale phase effects**

- **Programmatic applications**
  - **Low-Temperature Raleigh-Taylor Targets**
  - **Double-Shell Target**

- **Summary**

NIF will use 192 focused beams to perform energy research and HEDP experiments

Viewgraph courtesy of Maurice Aufderheide UNCLASSIFIED

We are benchmarking several different x-ray imaging systems for nondestructive characterization of HEDP targets

LLNL's KCAT

Advanced Light Source BL 8.3.2 DR/CT

Xradia 3D µXCT
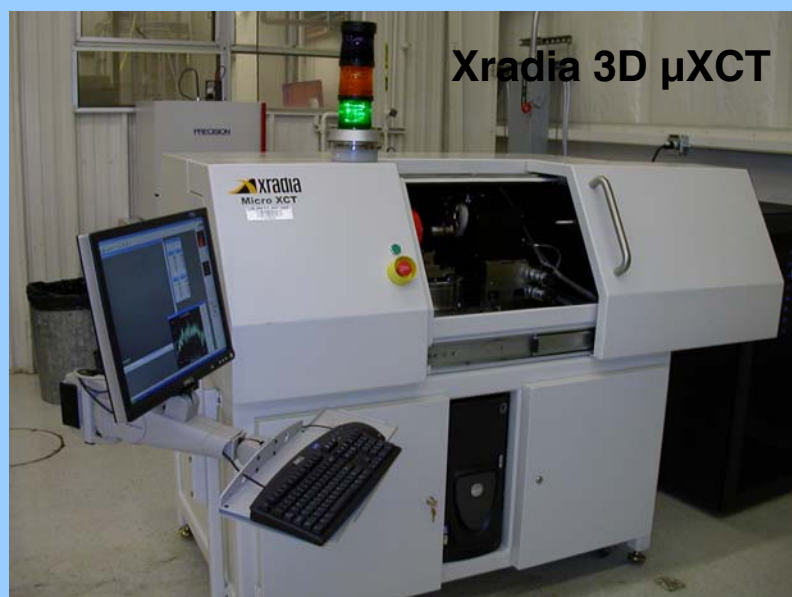
System Comparison

	LLNL KCAT	ALS Synchrotron	Xradia µXCT
X-ray Source	Kevex µ-focus	Synchrotron	Hamamatsu µ-focus
Energy	20 - 160 kV	6 - 30 keV	20 - 150 kV
Detector type	CCD	CCD	CCD
Scintillator	Tb doped glass	Cd_2WO_4	CsI
Camera pitch (µm)	9	9	13.5
Pixel size at detector (µm)	3	9.0 - 1.7	2.7/1.35/0.68

We are using MTF and SNR parameters of an edge as a measure of x-ray DR system performance

Side View

X-rays
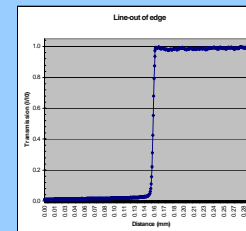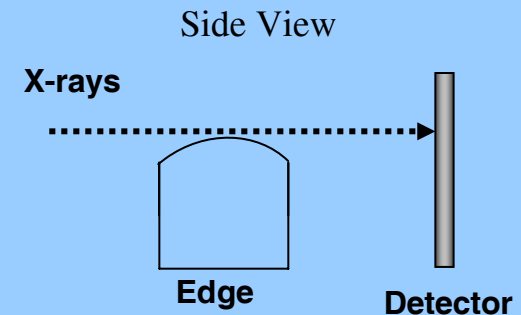
Edge   **Detector**

- **Modulation Transfer Function (MTF)**
  - **Frequency domain description of spatial resolution and contrast**
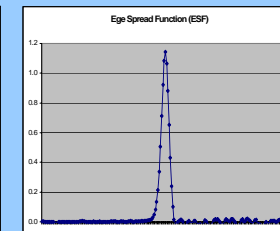 - **System MTF is the product of components**
    - **$MTF_{system} = MTF_{scintillator} * MTF_{optics} * MTF_{detector}$**

Edge   Derivative   Fourier transform

- **Signal to Noise Ratio (SNR)**
  - **Contrast measurement of images**
  - **SNR factors**
    - **Source noise**
    - **Detector noise**
    - **Scattered radiation**
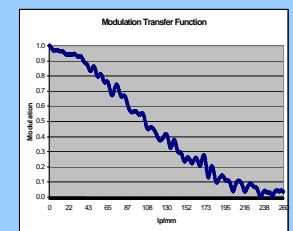
$$SNR = \frac{S_1 - S_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

S_1 = Mean of air σ_1 = Standard deviation of air
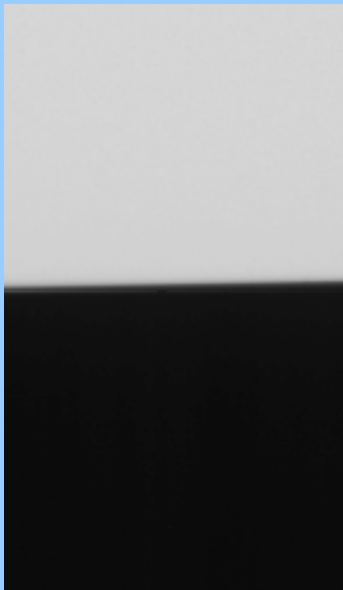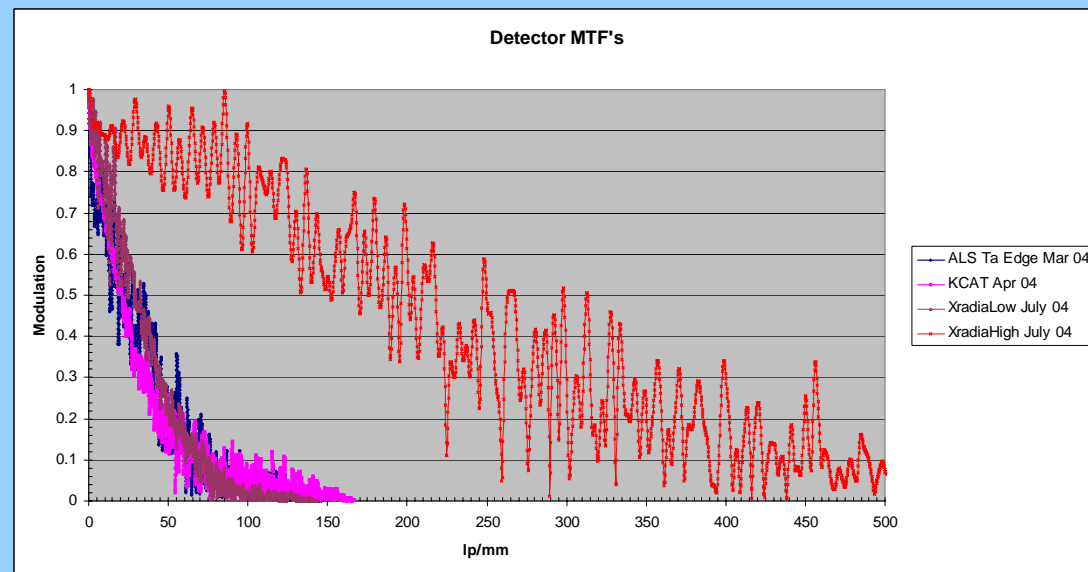S_2 = Mean of Cu σ_2 = Standard deviation of Cu

Comparison of DR MTF's showed the Xradia high resolution mode has the best MTF

Au(Cu) edge

DR of edge

Detector MTF's

Legend:
- ALS Ta Edge Mar 04
- KCAT Apr 04
- XradiaLow July 04
- XradiaHigh July 04

(Axes: Modulation vs lp/mm, 0 to 80)

Detector MTF's

Legend:
- ALS Ta Edge Mar 04
- KCAT Apr 04
- XradiaLow July 04
- XradiaHigh July 04

(Axes: Modulation vs lp/mm, 0 to 500)

UNCLASSIFIED
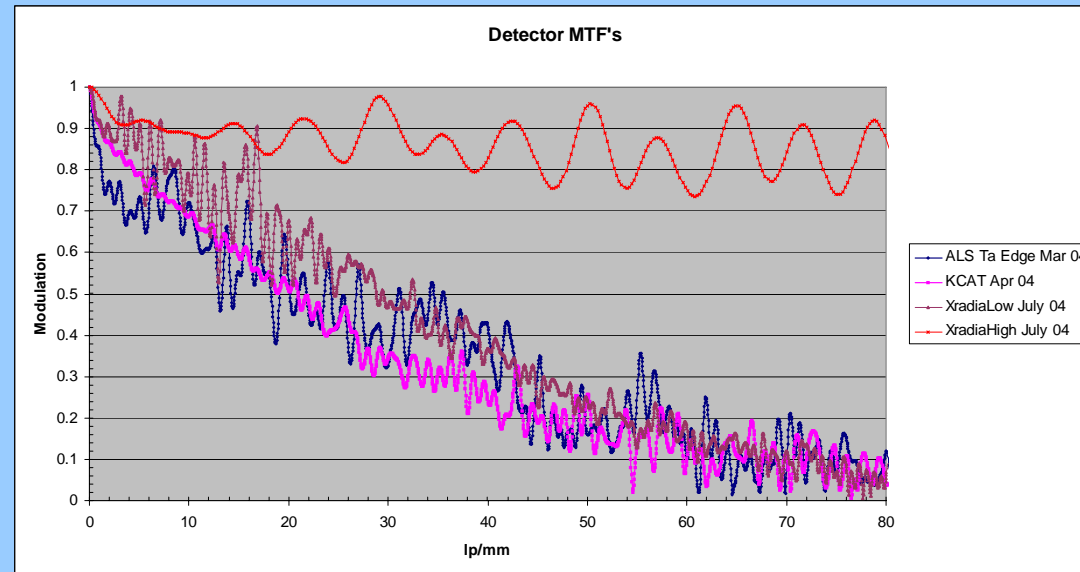
We are using MTF and SNR parameters of tubes as a measure of x-ray CT system performance

Top view

X-rays

Tube

Detector

- **Modulation Transfer Function (MTF)**
  — **Frequency domain description of spatial resolution**
  — **System MTF is the product of components**
    - MTF$_{system}$=MTF$_{scintillator}$*MTF$_{optics}$*MTF$_{detector}$*MTF$_{staging}$

Line-out of edge	Ege Spread Function (ESF)	Modulation Transfer Function

Edge   Derivative   Fourier transform

- **Signal to Nosie Ratio (SNR)**
  — **Contrast measurement of images**
  — **SNR factors**
    - **Source noise**
    - **Detector noise**
    - **Scattered radiation**
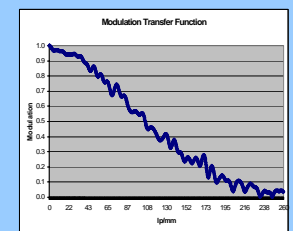
$$\text{SNR} = \frac{S_1 - S_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

S_1 = Mean of air σ_1 = Standard deviation of air
S_2 = Mean of Au σ_2 = Standard deviation of Au
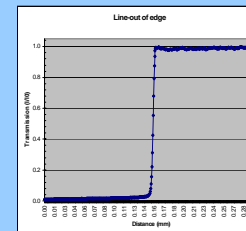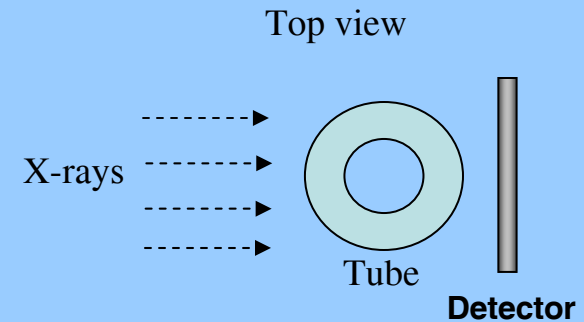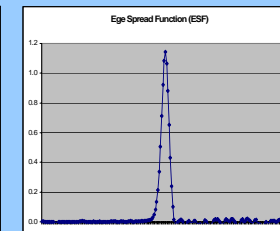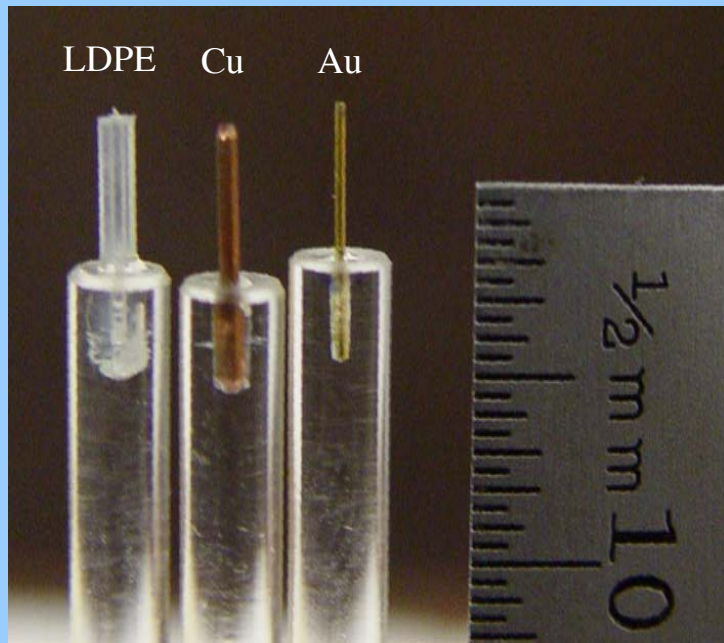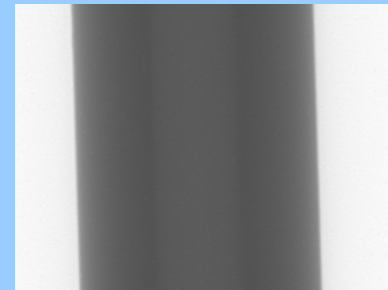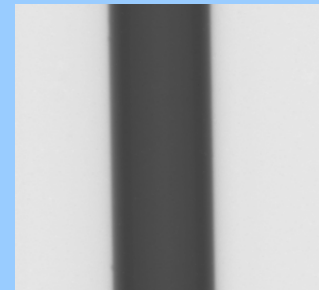
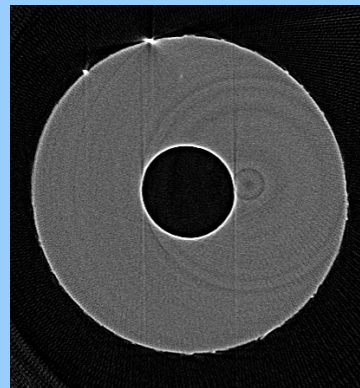# Three tubes are being used to measure x-ray CT system MTF's
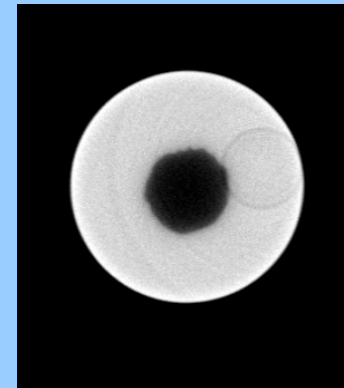

LDPE   Cu   Au
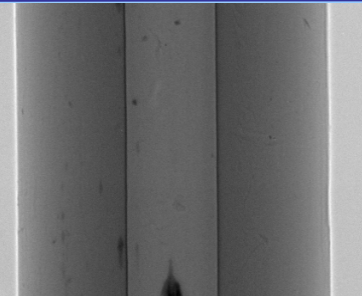
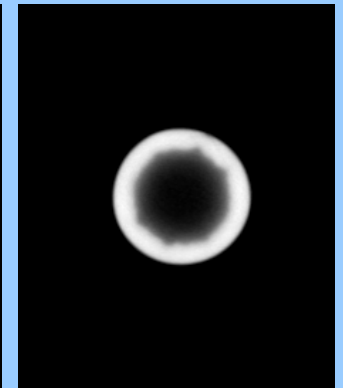LDPE

Copper

Gold

DR Transmission Images

LDPE

Copper

Gold

KCAT CT Images

Tube	Goodfellow specified outside diameter (mm)	Micrometer measured* outside diameter (mm)	CT measured outside diameter (mm)	Goodfellow specified wall thick (mm)	Mean CT measured wall thickness (mm)	Goodfellow Density (g/cm^3)
LDPE Δ	1.100	1.075±0.007	1.08±0.01	0.350	0.389±0.009	0.92
Cu	0.750	0.625±0.007	0.625±0.002	0.220	0.197±0.008	8.96
Au	0.300	0.270±0.007[+]	0.28±0.02	0.050	0.042±0.002	19.32

Comparison of CT OD and ID showed the OD has a greater MTF than the ID due to scattered radiation
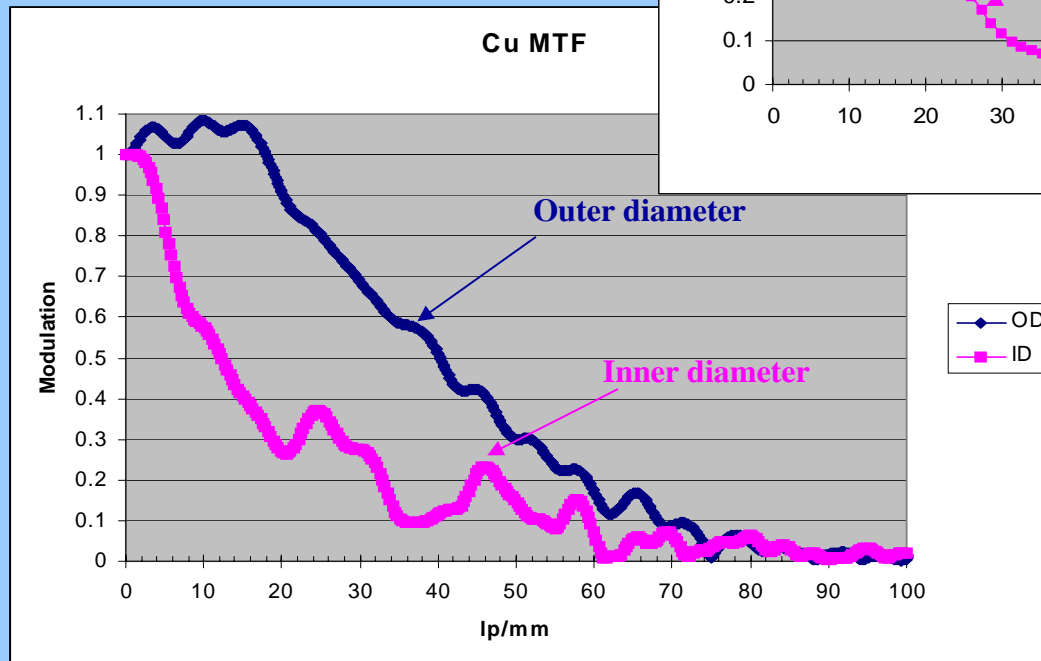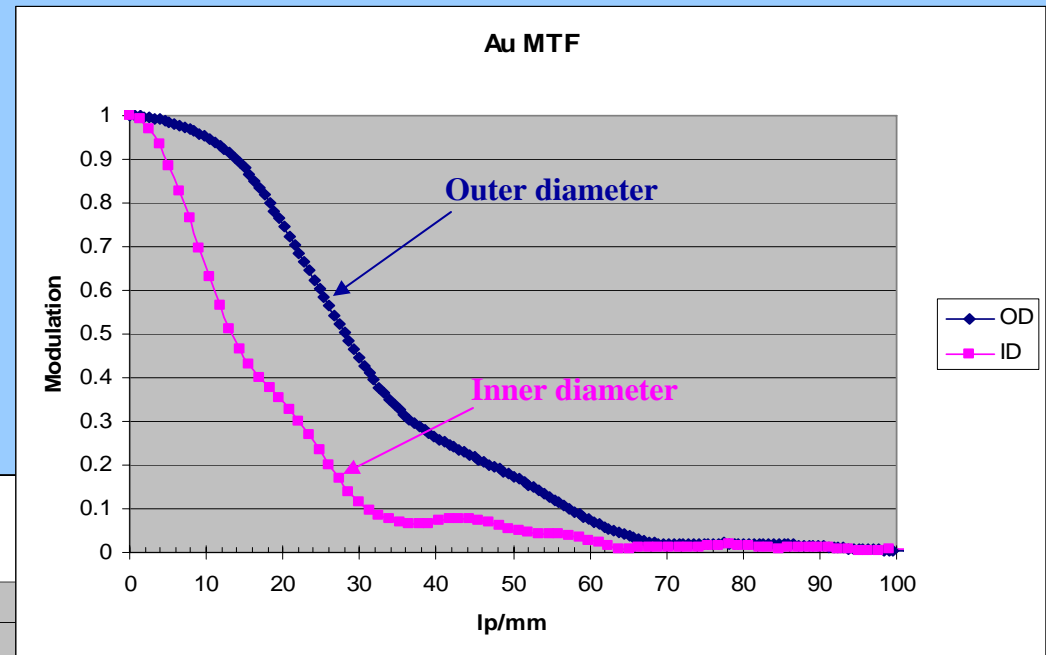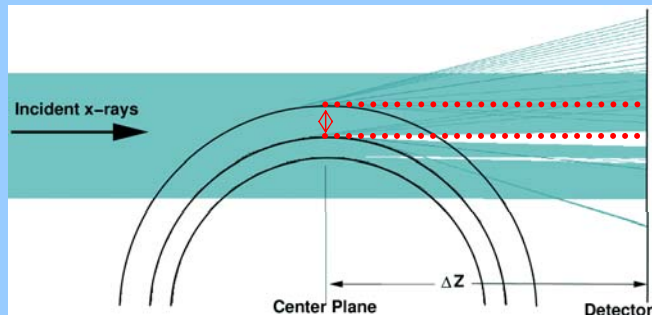

Copper

Gold

KCAT System

Au MTF

Modulation

Outer diameter

Inner diameter

OD
ID

lp/mm

Cu MTF

Modulation

Outer diameter

Inner diameter

OD
ID
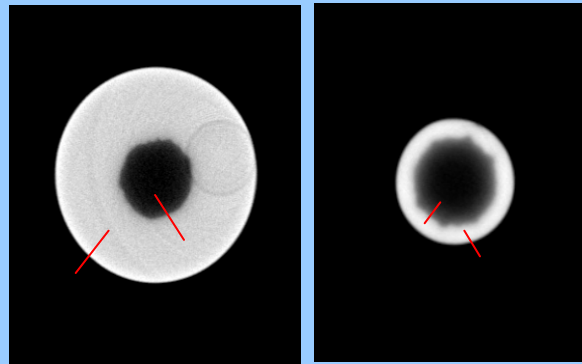
lp/mm

We need to quantitatively account for x-ray phase effects for accurate image analysis results

Incident x-rays

Center Plane   ΔZ   Detector

Phase effects can generate dimensional errors

- 8 kev
- 10 keV
- 20 keV
- 30 keV

Diamond inner wall

Diamond outer wall

Normalized Intensity

Radial Position (µm)

Phase effects change with
- **Object materials & geometry**
- **Source-object-detector geometry**
- **Source energy**
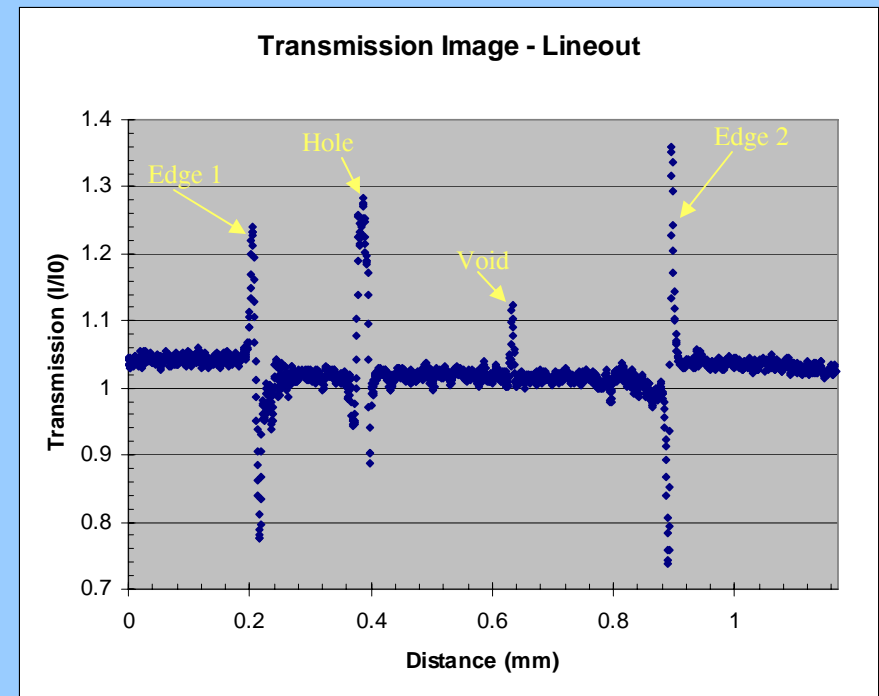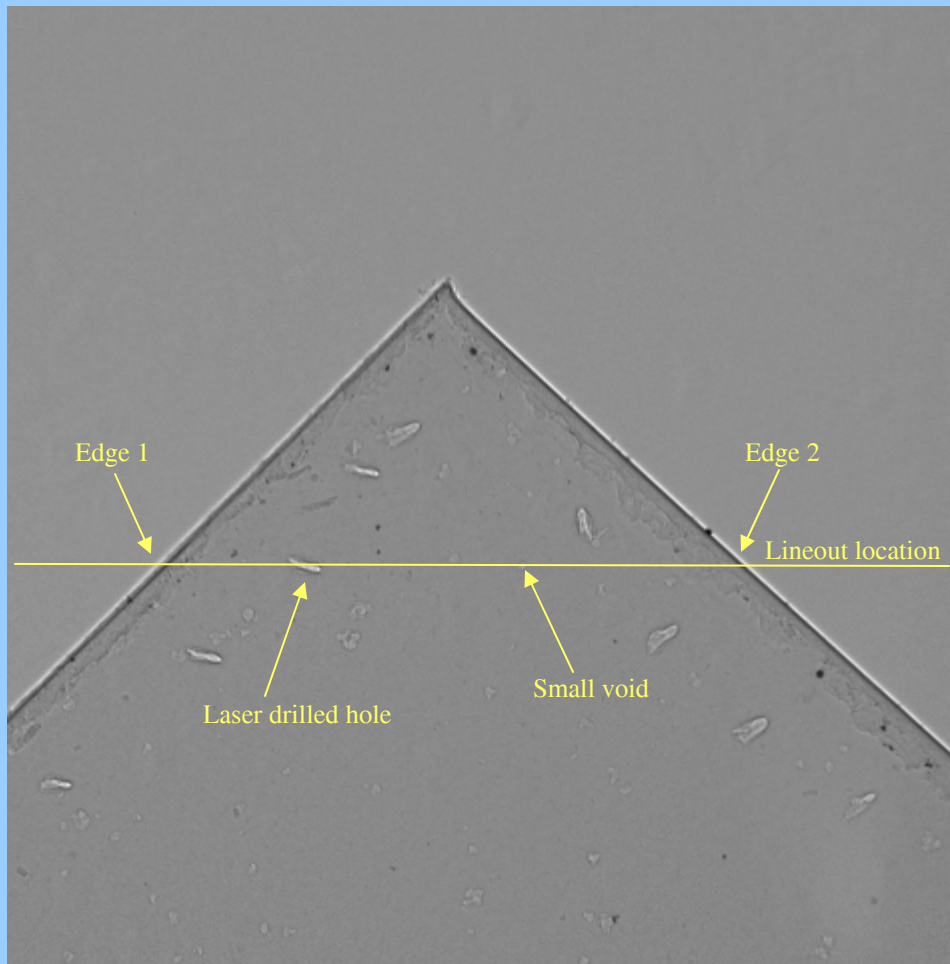- **Spatial resolution**

Phase effects can generate
- **Dimensional errors**
- **Fictitious gaps**
- **Wrong material identification**
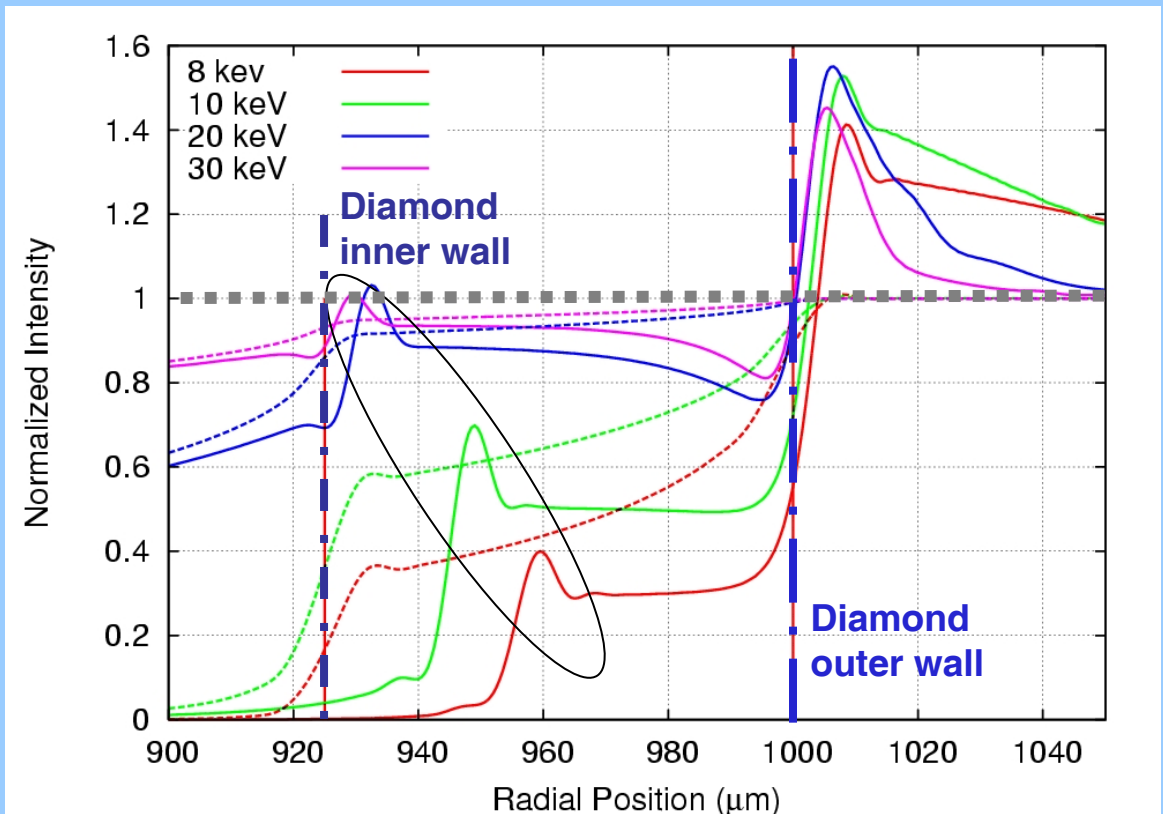
Phase effects impact both radiographic and tomographic x-ray imaging

A transmission (I/I0) radiograph of a Be strip with Lineout Illustrates x-ray phase effects

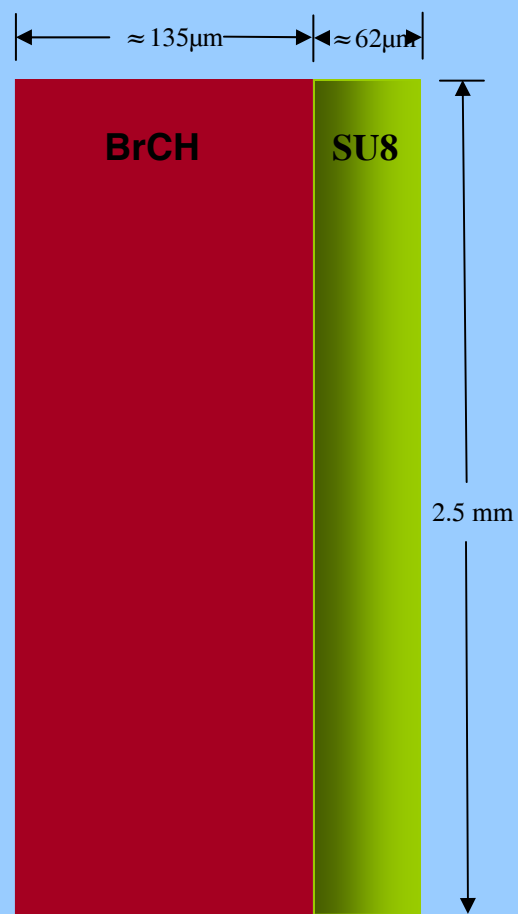

Transmission Image - Lineout

DR parameters: 60kV, 0.066 mA
100 sec/frame, 1 frame average
SDD=68.2mm, SOD=55.7mm
20X objective FOV: 1.2 mm X 1.2 mm
1X1 Binning; 0.582 μm pixel pitch

Image binned 4X4 for VG

Schematic of gradient density reservoir

≈135μm ≈62μm

BrCH   SU8

2.5 mm

Side View

BrCH

≈135μm

SU8

≈62μm

Top View

Picture of sample

Gradient reservoir

Sample mount

~18mm

Xradia mount
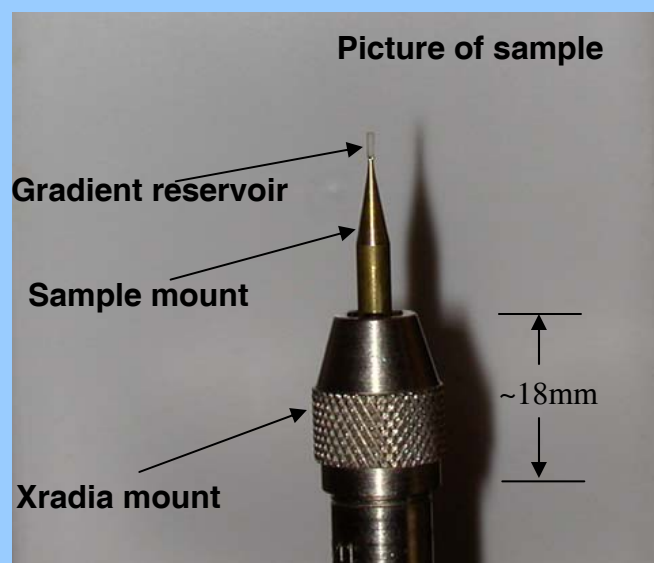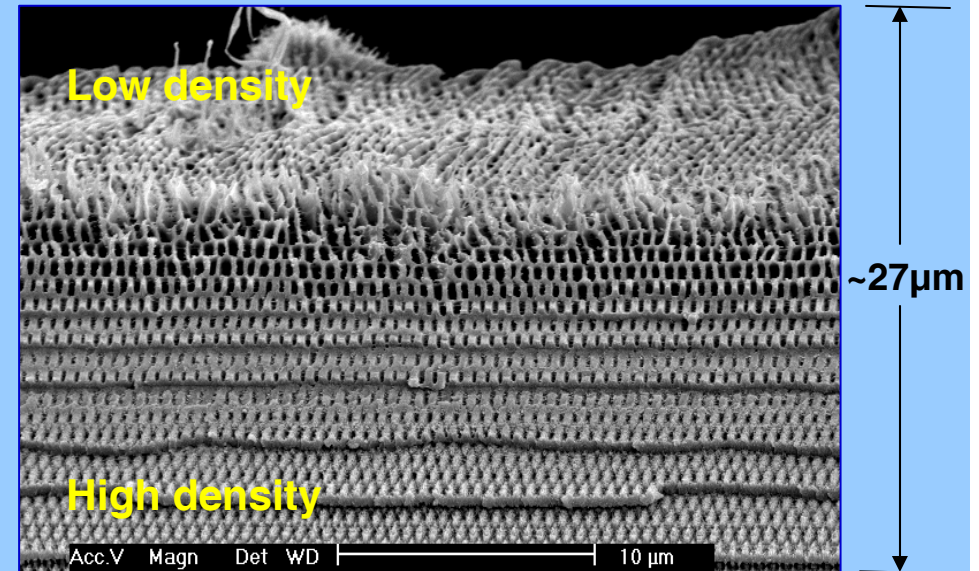
Photolithography is used to make graded density SU8

~62 μm

Low density

High density

~27μm

Acc.V   Magn   Det WD   10 μm

SEM image of SU8

Full sample is made of 60 layers of photosensitive SU8

The photosensitive SU8 is photolithographically patterned and developed
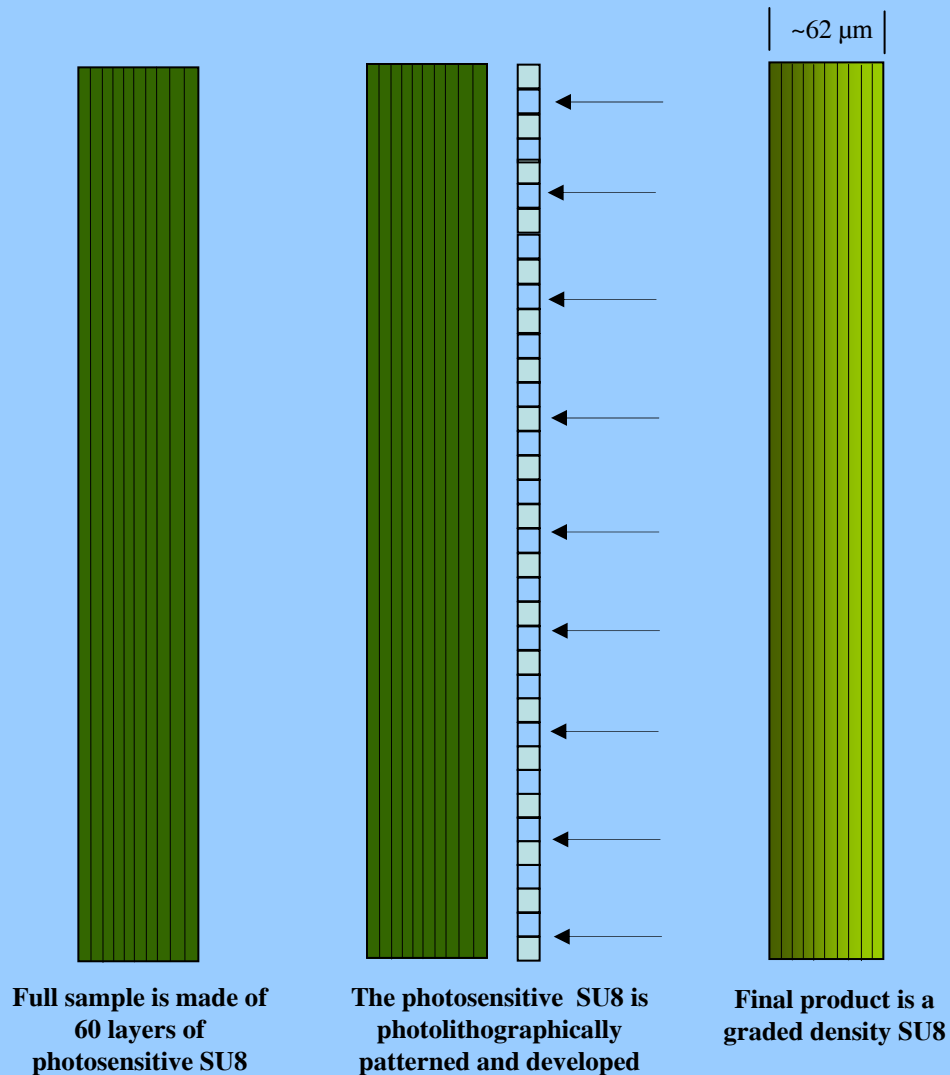
Final product is a graded density SU8

DR image and lineout thru sample showing graded density with peak and valley anomalies

BrCH ← → SU8

Approx. lineout location
(7 line avg)
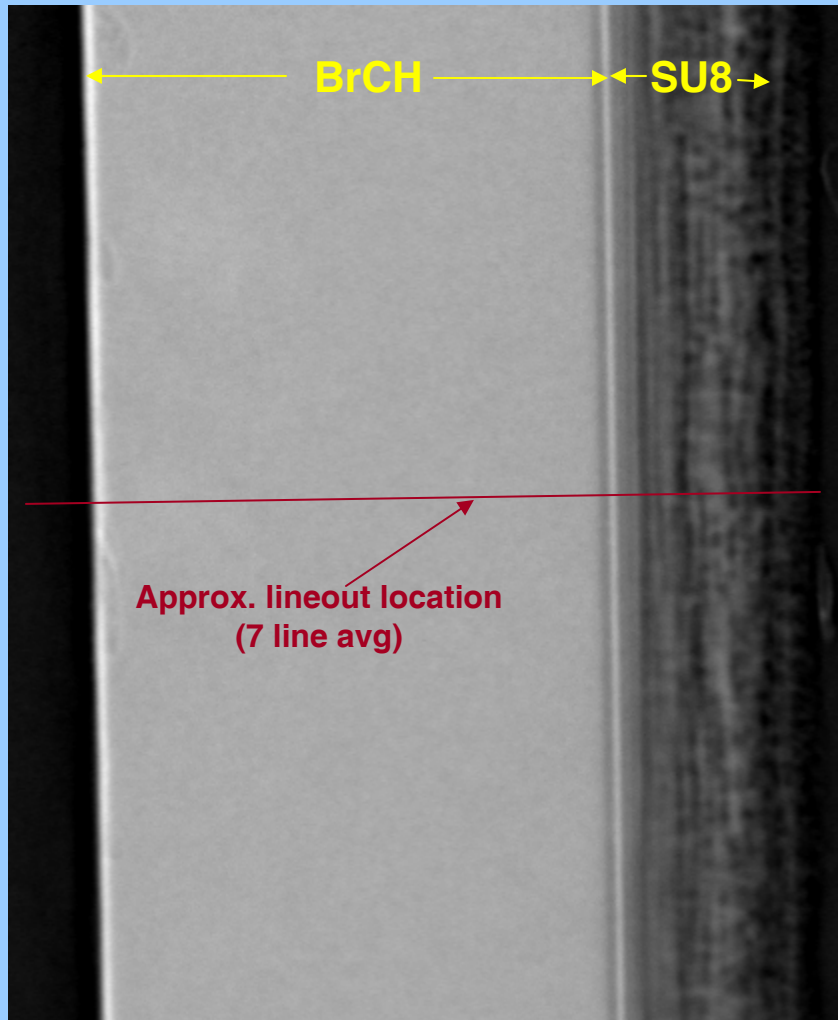
Xradia image
Image scaled to fit VG

Lineout thru sample- sample 3
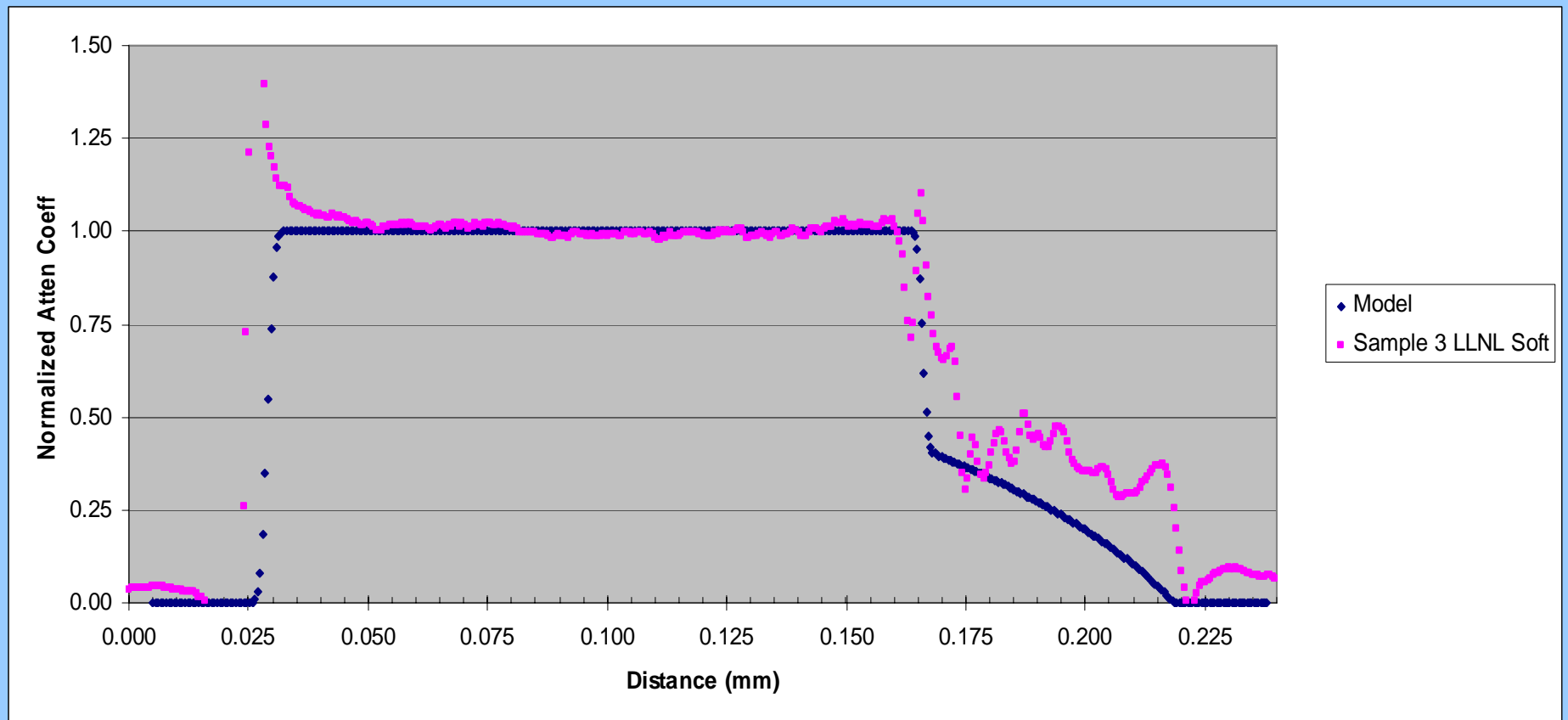

Lineout thru gradient
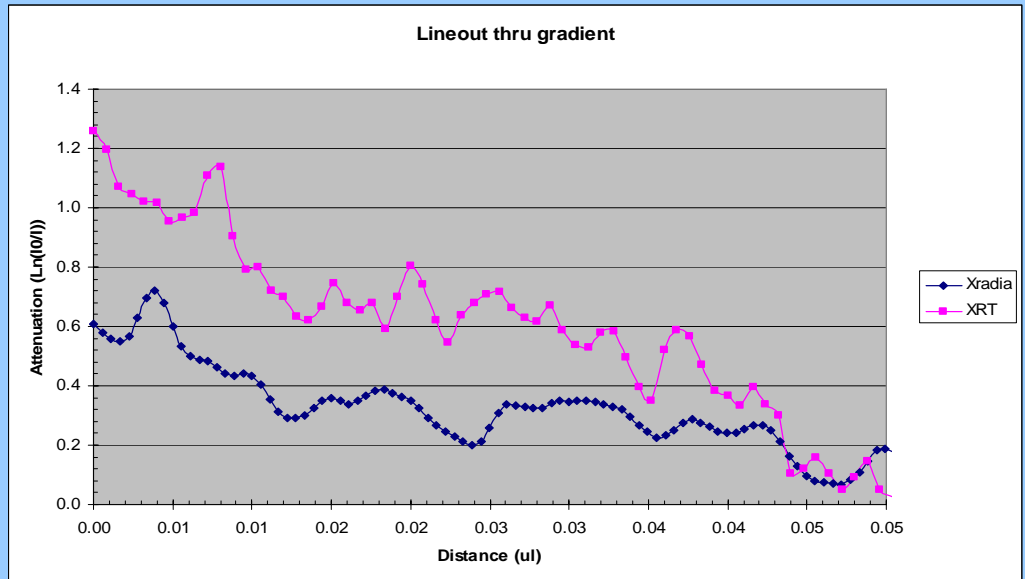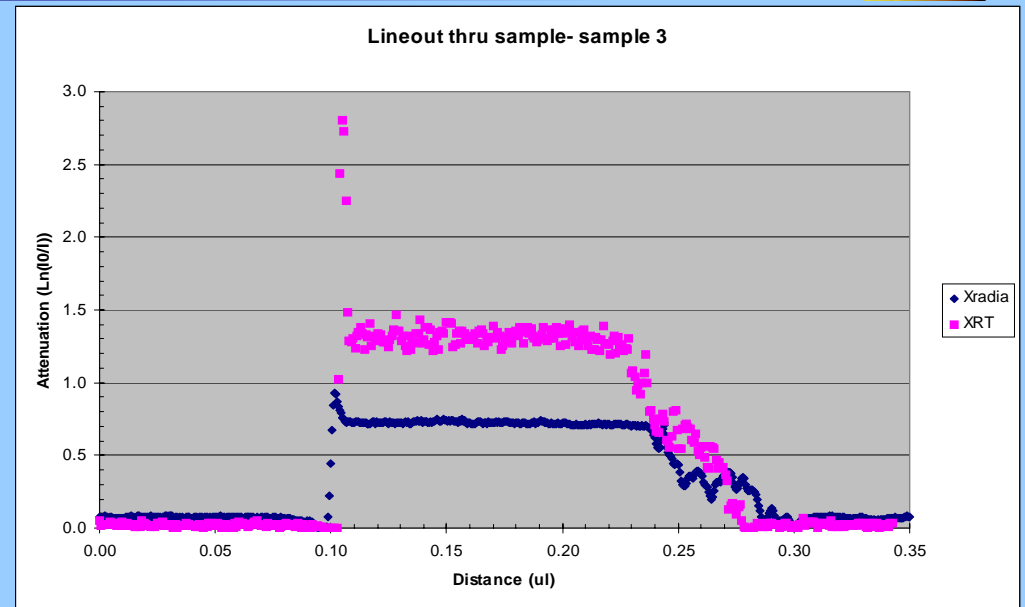
Computed tomography image reveals a density gradient and artifacts from the phase effects
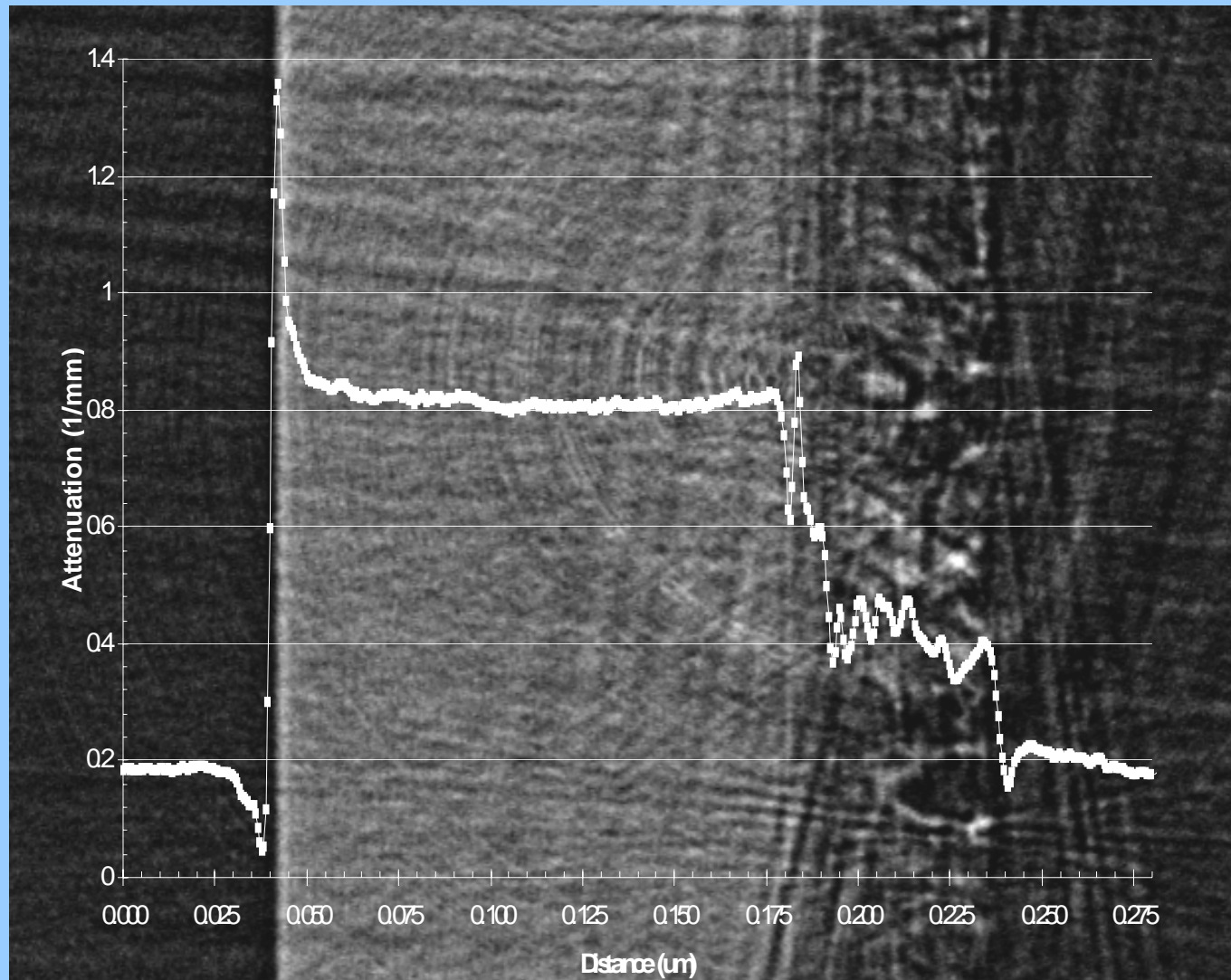
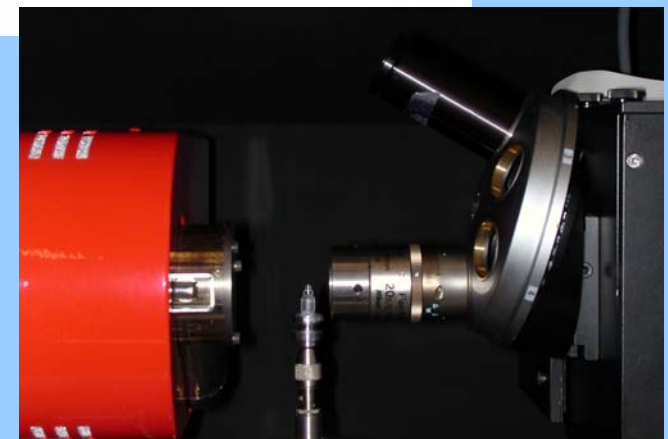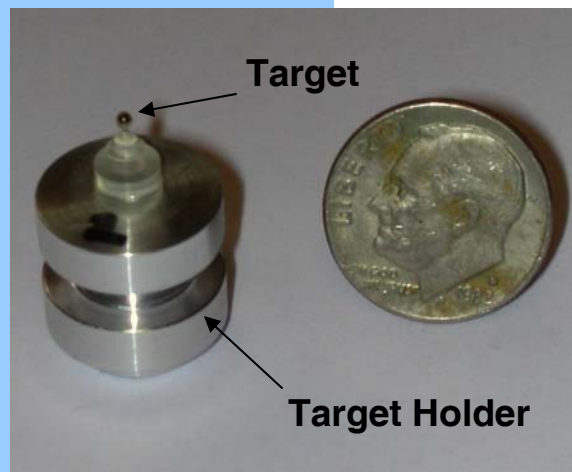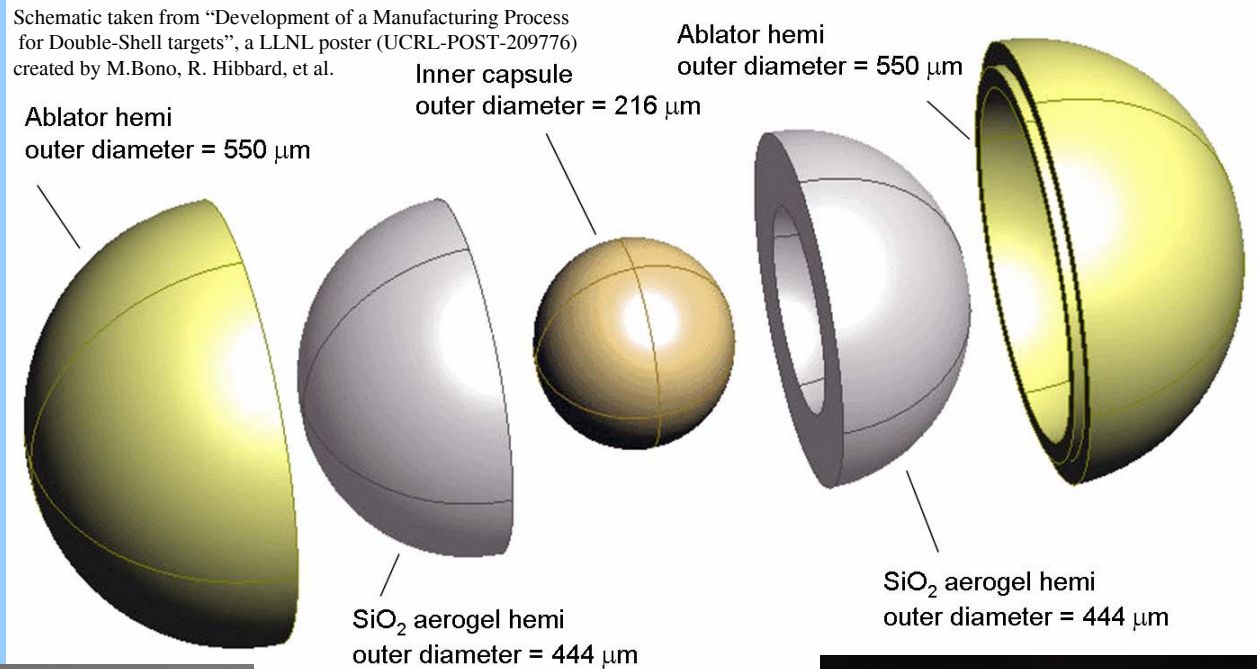Artifacts make it difficult to quantify the density gradient

# HADES simulations are being used to interpret the empirical data

The results reveal more work is needed

Both model and Xradia data normalized

A double shell is a complicated target with many critical dimensions
2004 design included 2 aerogel hemis

Schematic taken from "Development of a Manufacturing Process for Double-Shell targets", a LLNL poster (UCRL-POST-209776) created by M.Bono, R. Hibbard, et al.

Ablator hemi outer diameter = 550 μm

Inner capsule outer diameter = 216 μm

Ablator hemi outer diameter = 550 μm

SiO_2 aerogel hemi outer diameter = 444 μm

SiO_2 aerogel hemi outer diameter = 444 μm

Target

Target Holder

Attenuation radiograph of double shell targets revealed small voids between aerogel hemis in limited angles

Ablator

Inner capsule

SiO_2 aerogel
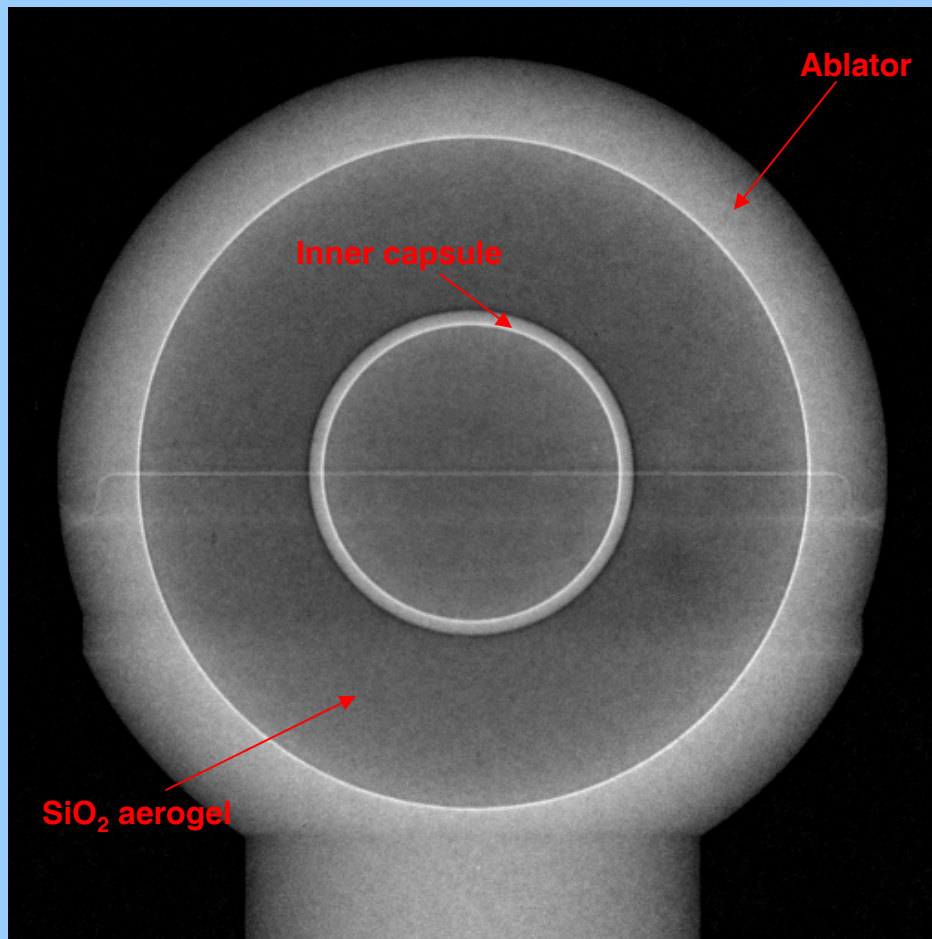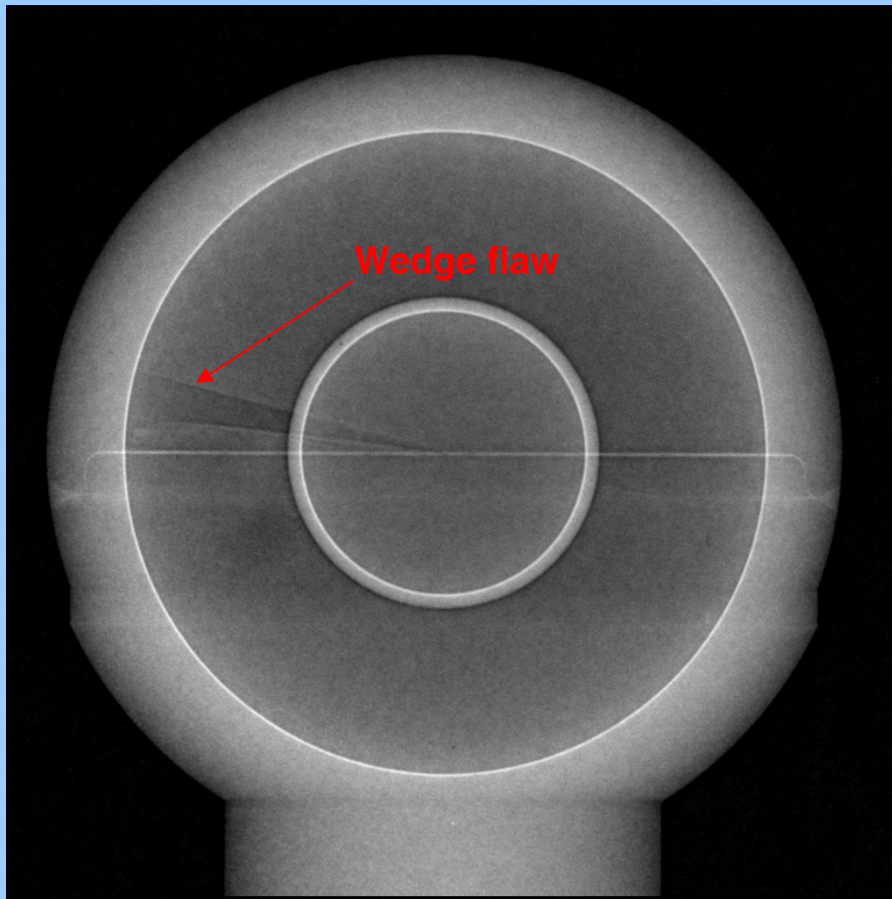
Attenuation radiograph 0 degrees
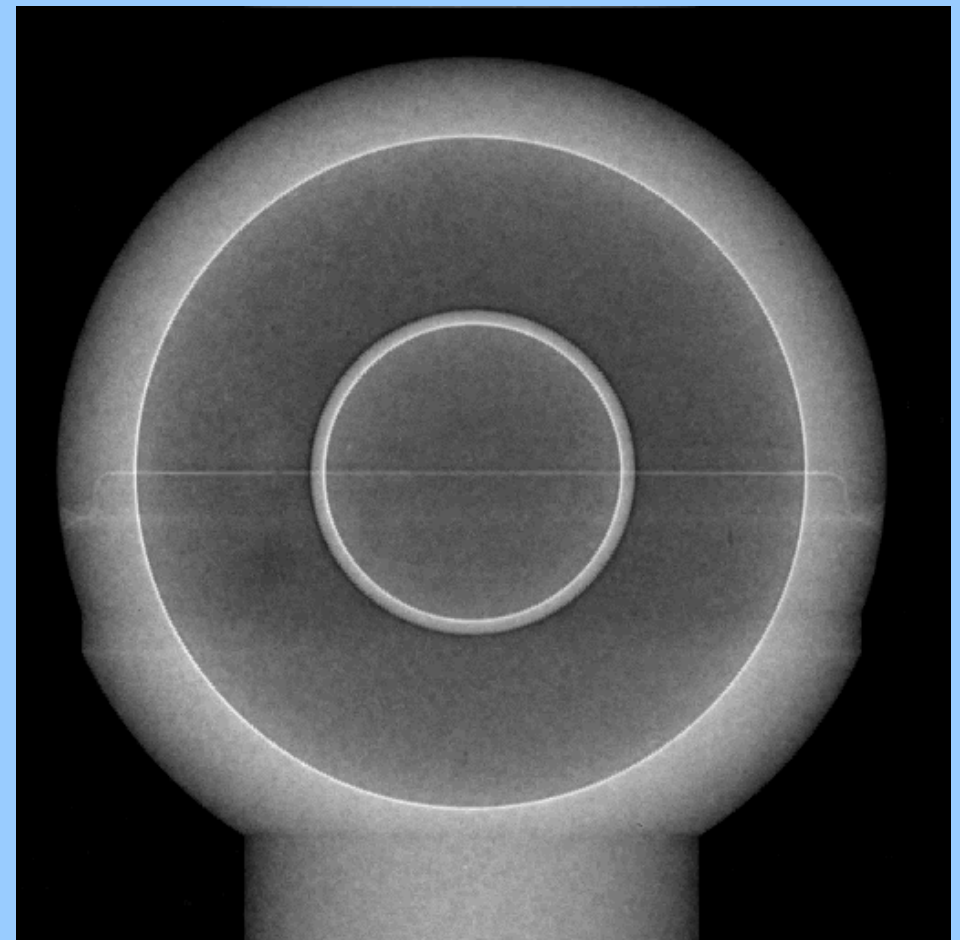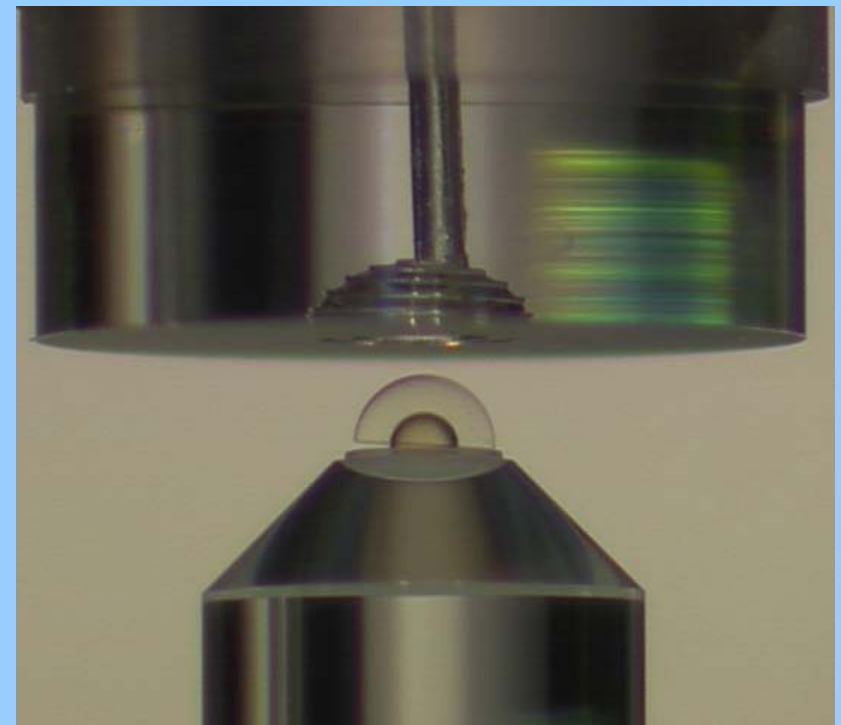
Click on image to begin movie

Review of the manufacturing process reveals why the flaw may have occurred

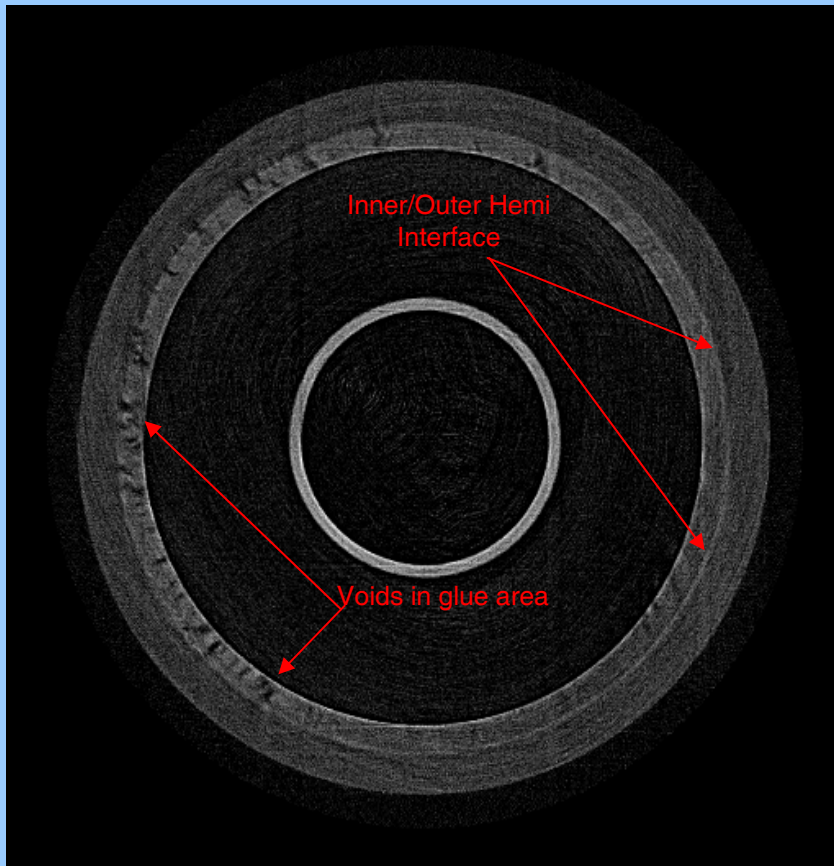**μXCT Attenuation images (ln I$_0$/I) DS #7**

Wedge flaw
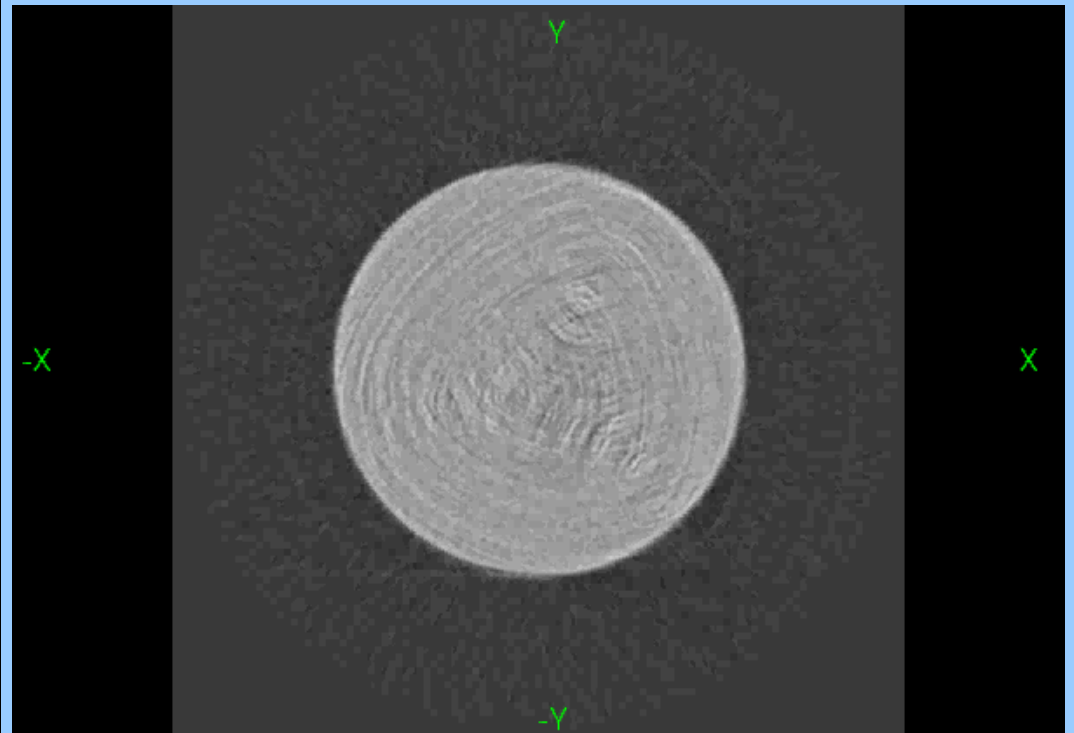
Photograph of assembly DS #7

μXCT data acquired on Dec 13, 2004
pixel size ~600 nm (1 x 1 binning)
Both I and I$_0$ images were 1 DR avg. 60 sec. ea.
sod 170 mm odd 10 mm

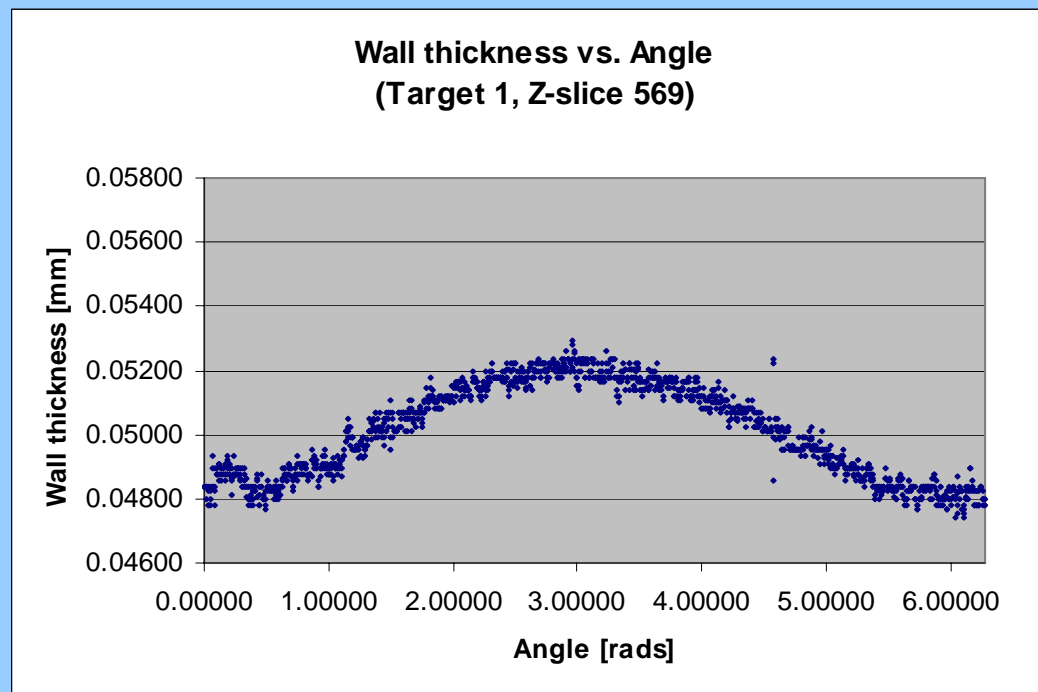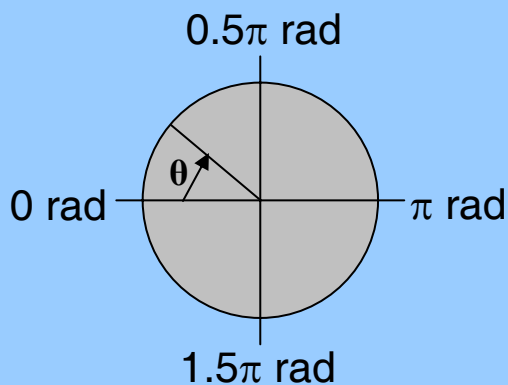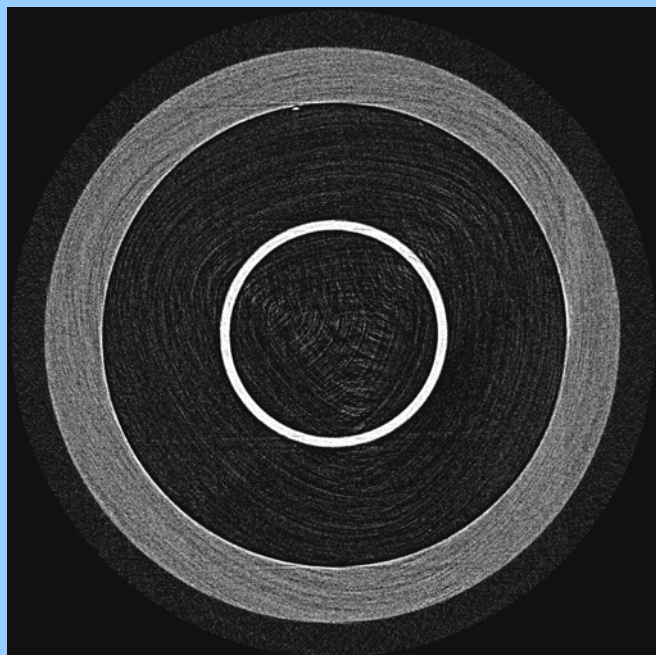# We use tomography to obtain full volumetric characterization

XY plane tomography image

Click image to start movie

We were able to accurately measure wall thickness

Wall thickness vs. Angle
(Target 1, Z-slice 569)

0.5π rad

0 rad — θ — π rad

1.5π rad

| TARGET	GLOBAL[1] [185º, 355º]				POLE[2] [269º, 271º]	
	MEAN [µm]	STD DEV [µm]	MAX [µm]	MIN [µm]	MEAN [µm]	STD DEV[3] [µm]
1	51.14	0.47	52.20	49.52	51.22	0.00
2	49.59	0.35	50.44	48.46	49.73	0.25
3	51.56	0.61	52.52	49.68	51.52	0.28
6	50.37	0.46	51.63	48.95	49.94	0.18
7	54.39	0.46	55.86	53.24	53.86	0.00
8	49.92	0.53	51.22	48.38	50.07	0.06

As a result of our DR/CT, a new fabrication technique was developed to remove the wedge flaw by casting the inner sphere in aerogel
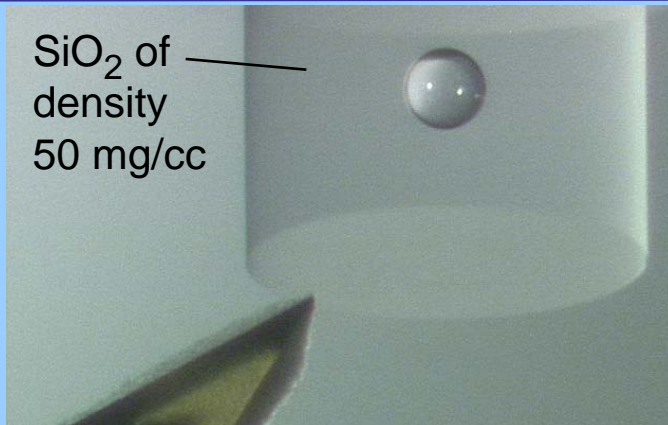
SiO_2 of density 50 mg/cc

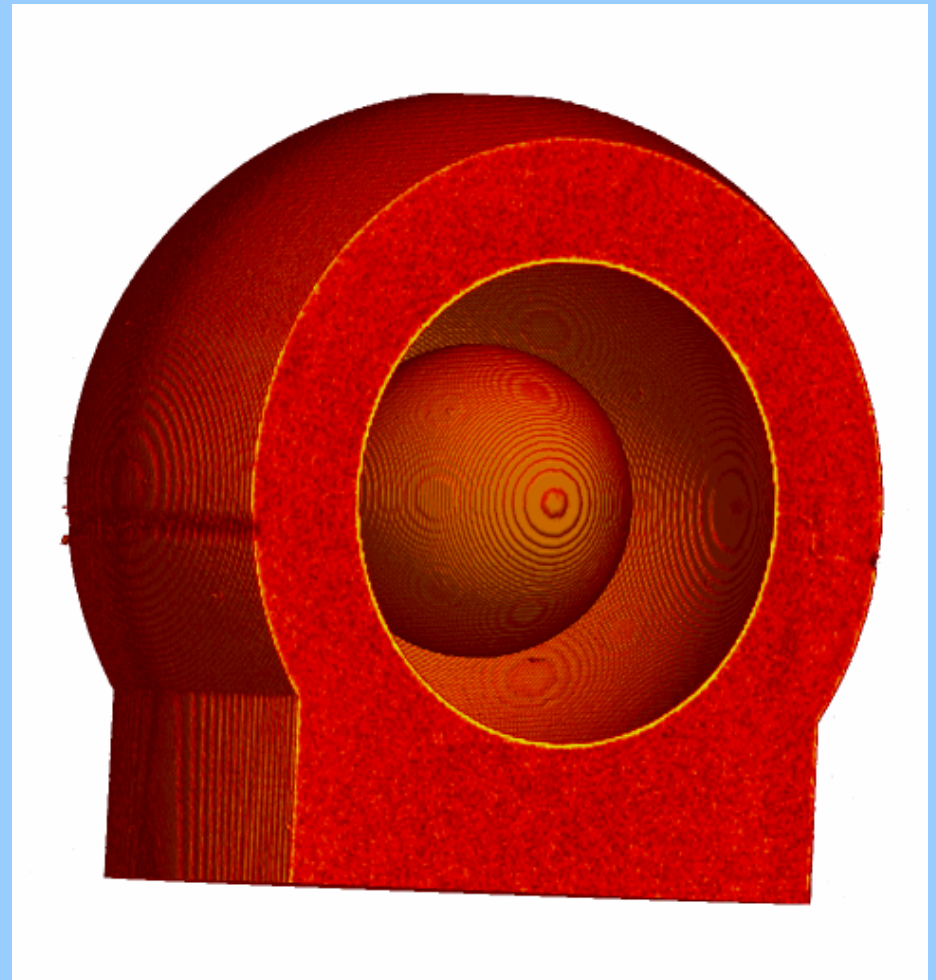Capsule was centered using a vision system on the machine tool.

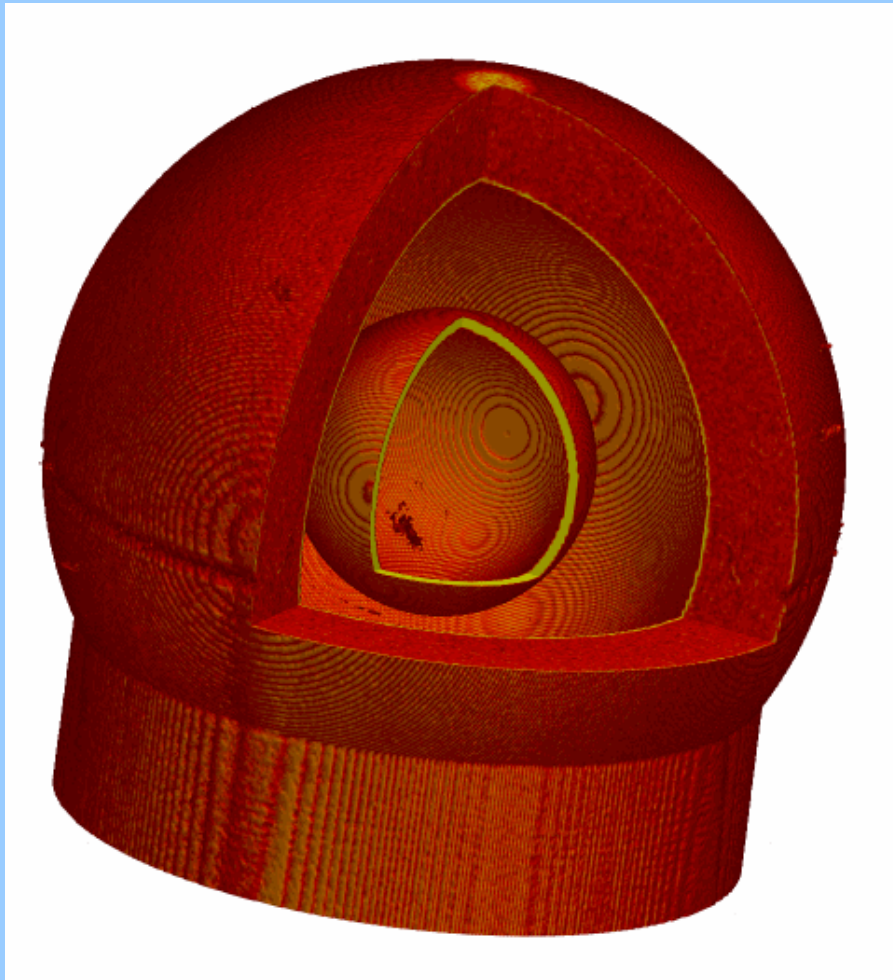SiO_2 was machined concentric to the capsule.
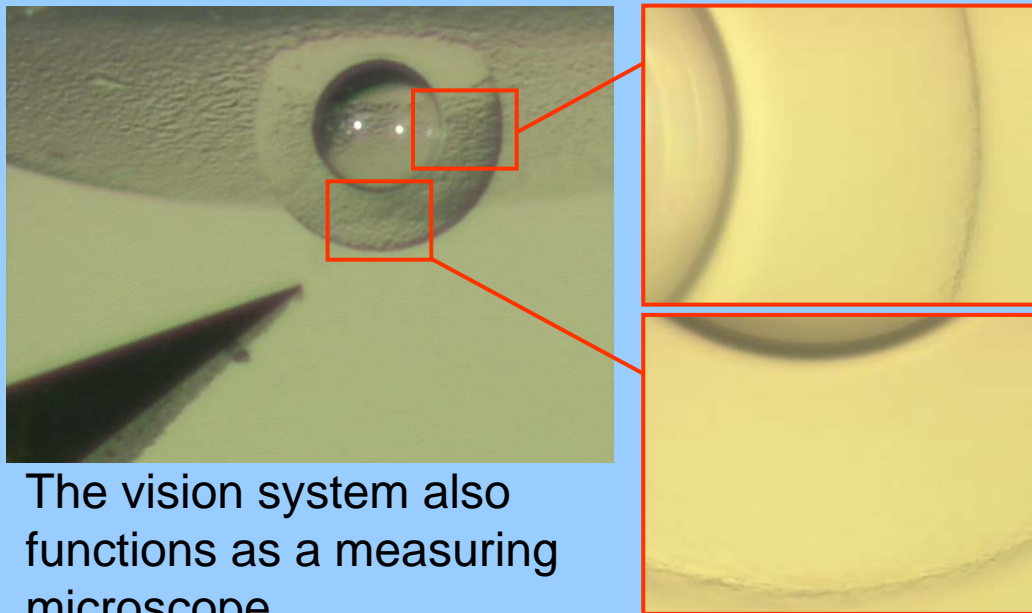
The vision system also functions as a measuring microscope.

Viewgraph courtesy of Matt Bono

Volumetric rendering of double shell with new design confirmed the elimination of the wedge type flaws

Summary

- We have used x-ray DR and CT measurements to develop fabrication processes that meet target specifications

- We have also used x-ray images for metrology and quality control

- We are using DR and CT MTF's and SNR parameters to benchmark many different x-ray point projection systems

- Phase effects need to be considered in mesoscale imaging. We are developing object recovery algorithms to obtain an accurate object recovery
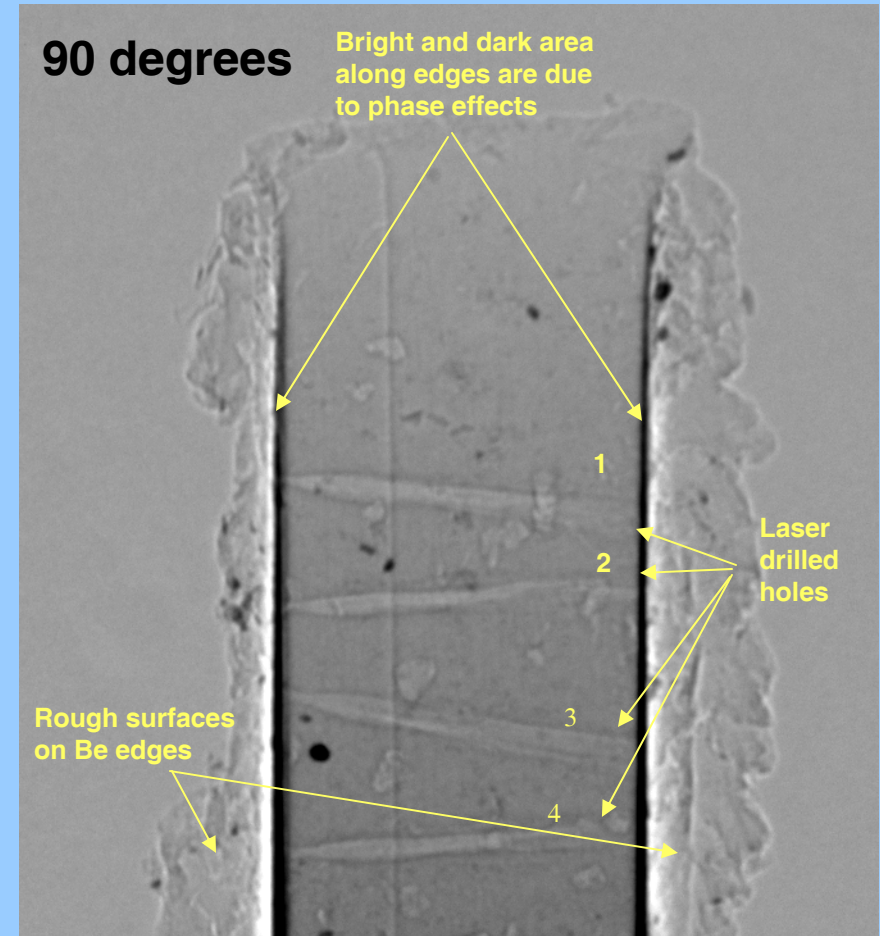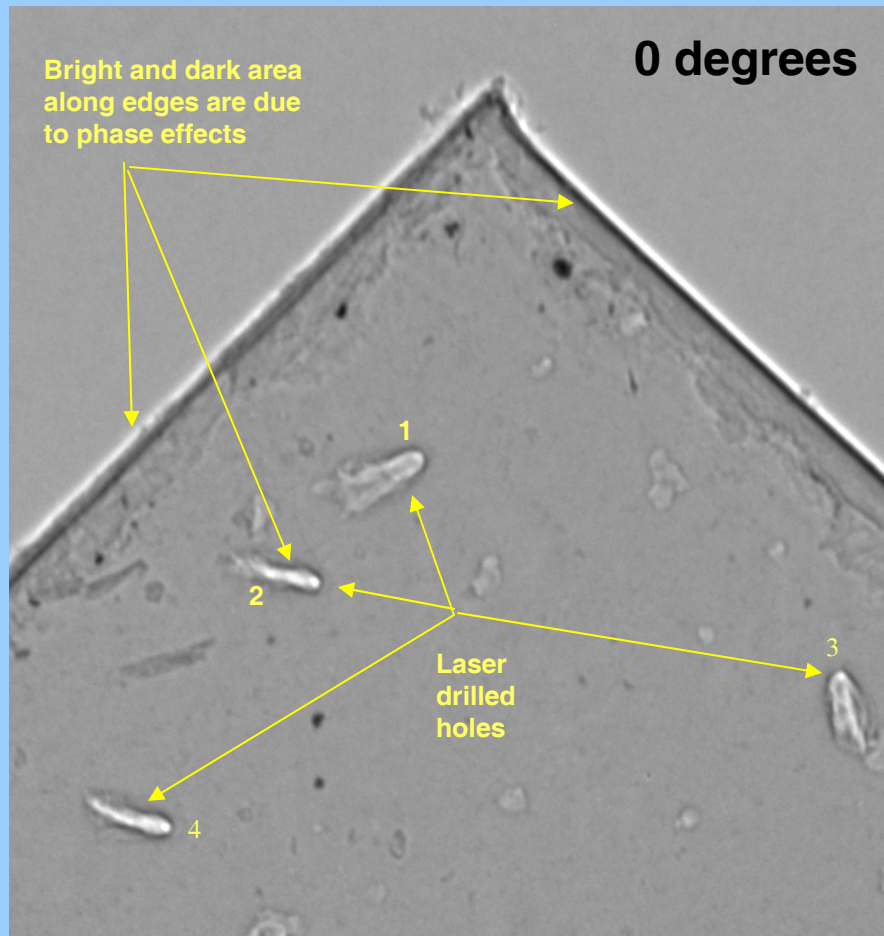
Backup Slides

Transmission image (I/I_0) of Double Shell showing inner SiO_2 and outer aerogel sphere with line-out
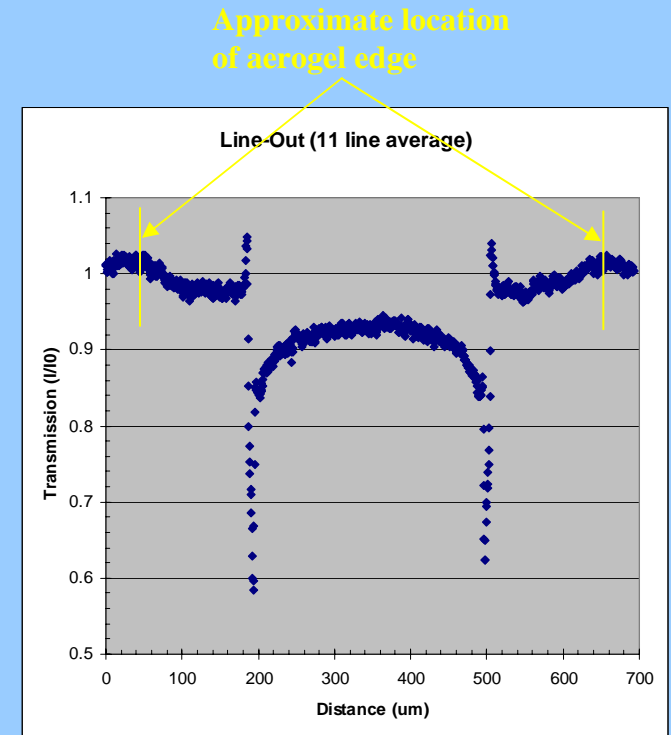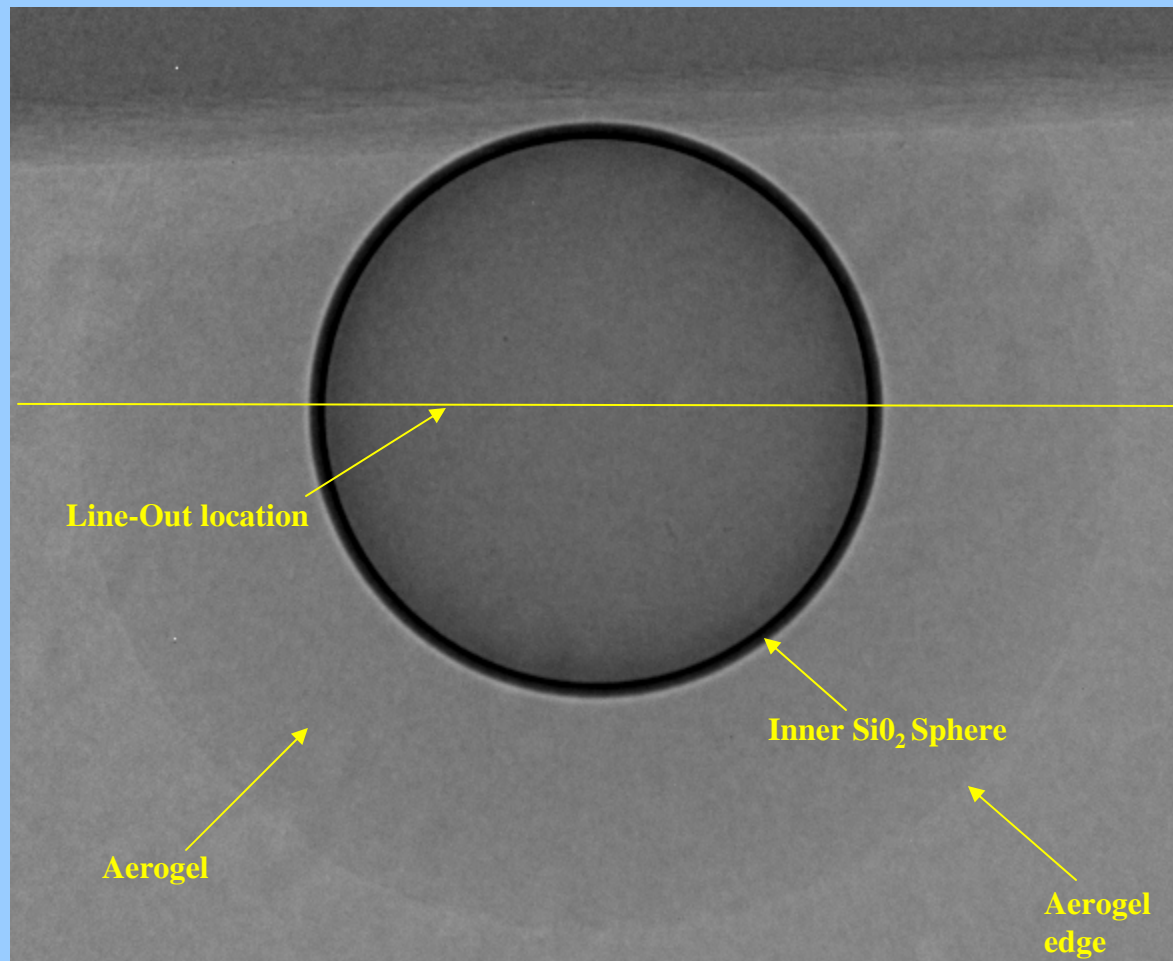
120 kVp, 0.033 mA
30 Sec Integration
20X FOV Setting (1.4 mm X 1.4 mm)
1 X 1 Binning, 1 Frame Avg
68.0 mm SDD, 55.7 mm SOD, pixel pitch 0.554μm

Transmission* (I/I$_0$) radiograph of Be strip with laser drilled holes – Images cropped for VG

0 degrees

Bright and dark area along edges are due to phase effects

Laser drilled holes

1

2

3

4

90 degrees

Bright and dark area along edges are due to phase effects

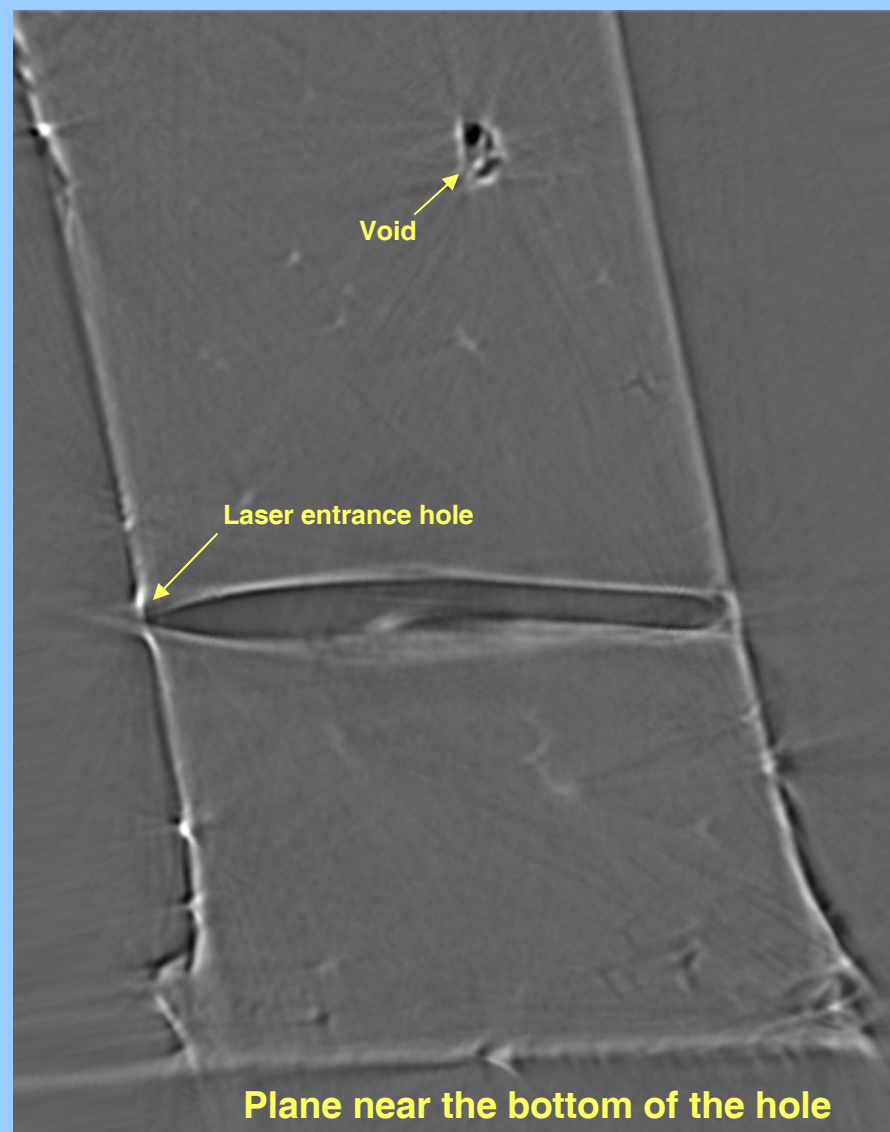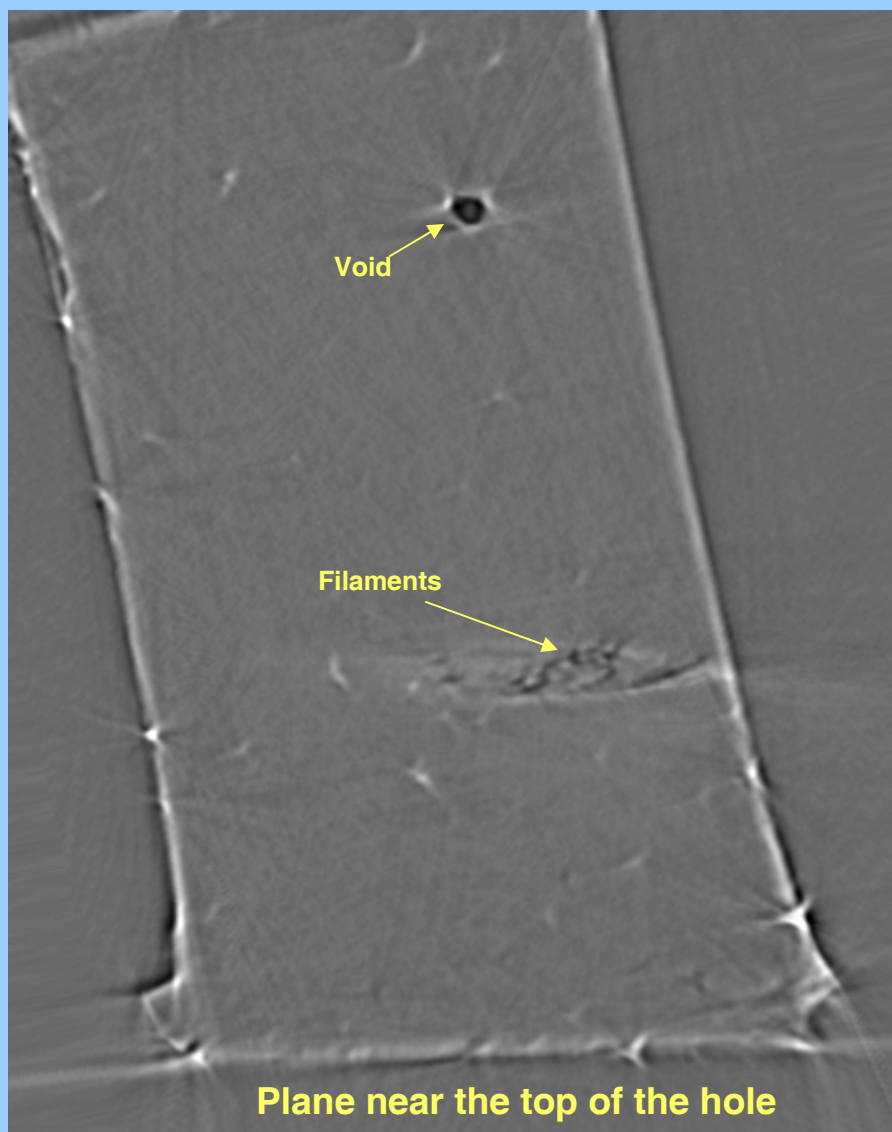Laser drilled holes

Rough surfaces on Be edges

1

2

3

4

DR parameters: 60kV, 0.066 mA
100 sec/frame, 1 frame average
SDD=68.2mm, SOD=55.7mm
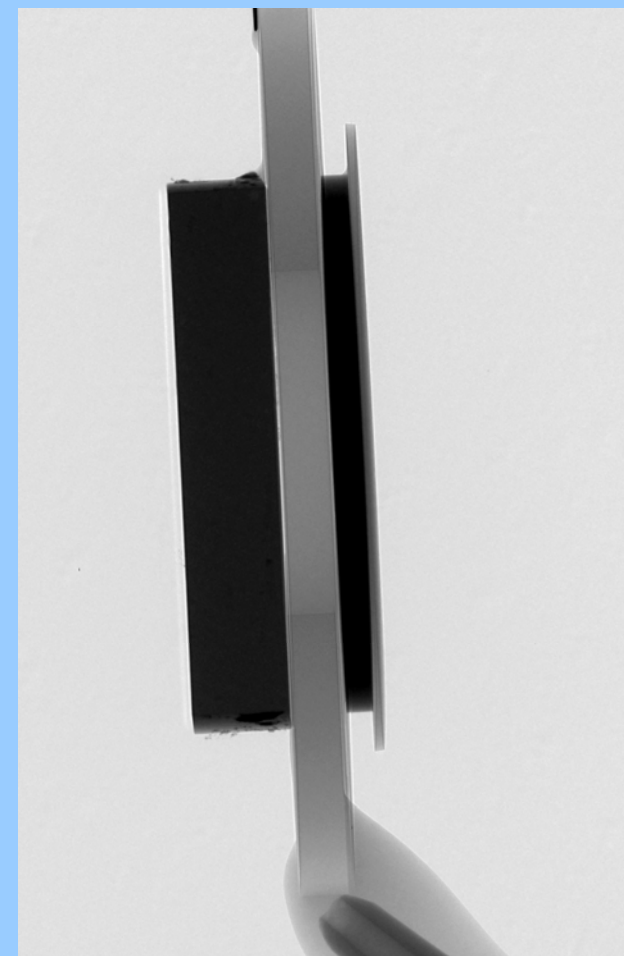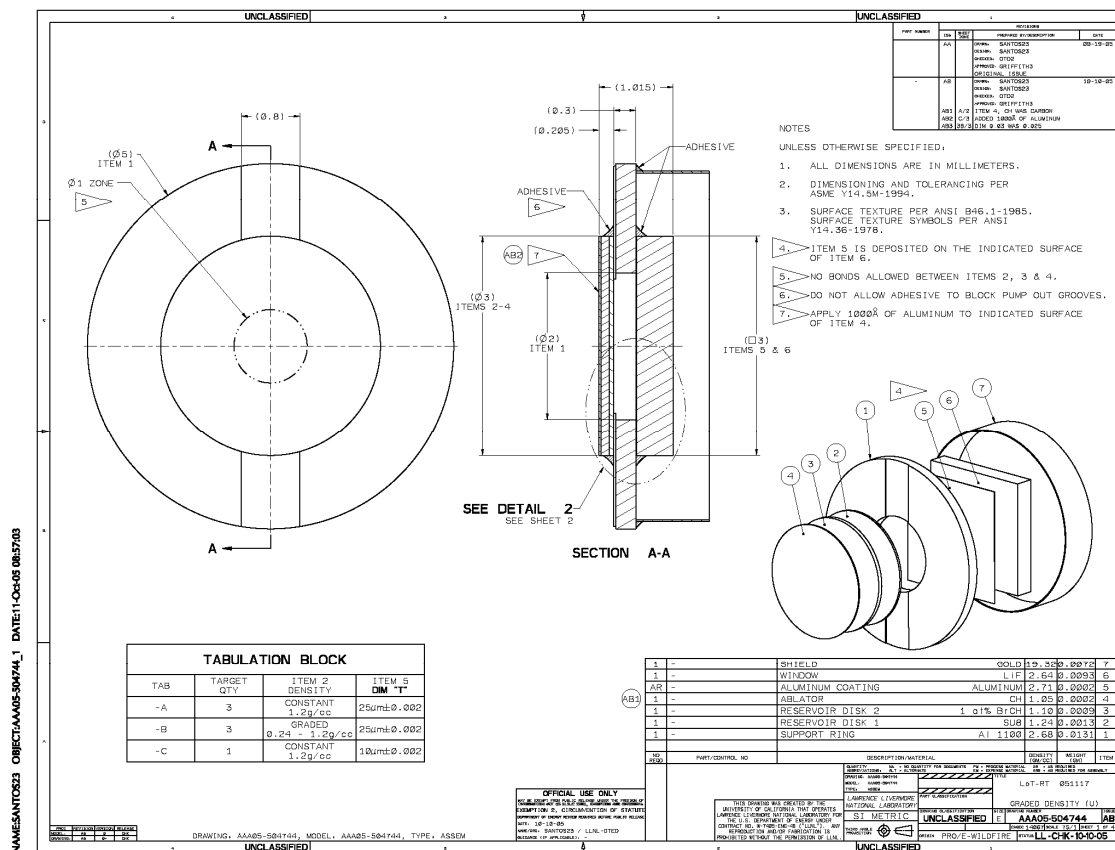20X objective FOV: 1.2 mm X 1.2 mm
1X1 Binning; 0.582 µm pixel pitch

$$*T=I/I_0=\exp{-(\mu l)}$$

Void

Filaments

Plane near the top of the hole

Void

Laser entrance hole

Plane near the bottom of the hole
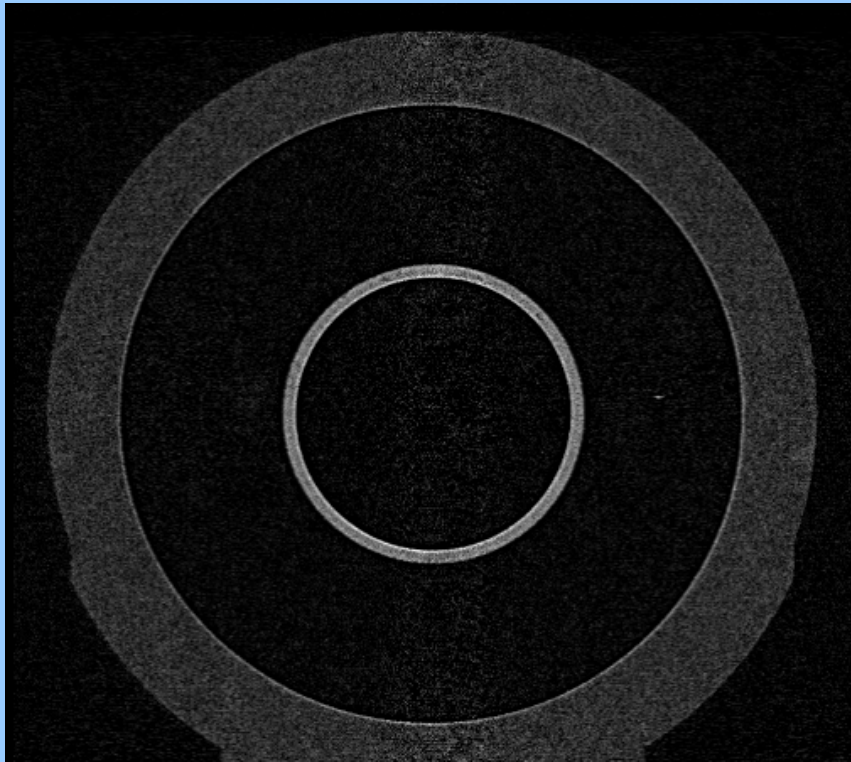
Transmission image (I/I0)

Image cropped and 4x4 binned

90 kV, 0.067 mA
120 Sec Integration
5X FOV Setting (5.4 mm X 5.4 mm)
1 X 1 Binning, 1 Frame Avg
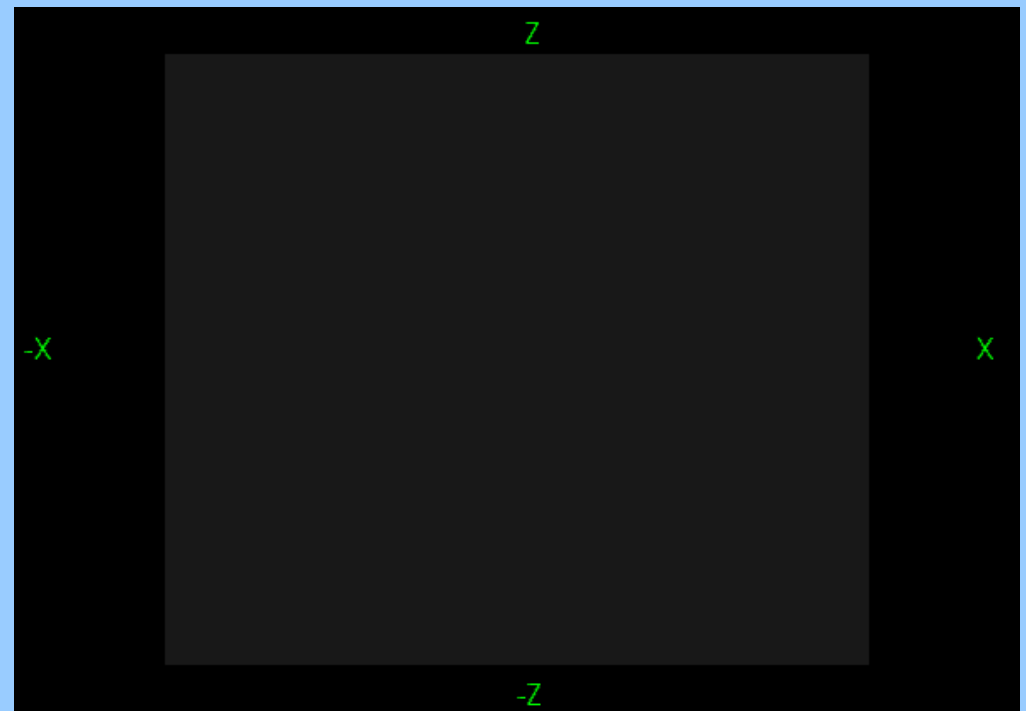202 mm SDD, 197 mm SOD, pixel pitch 2.7μm

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We use tomography to obtain full volumetric characterization

YZ plane tomography image

Click image to start movie

Concentricity values for 6 Double Shell targets

Target Number	Avg Pixel Size (Microns)	Avg X Coord Outer Sphere	Avg Y Coord Outer Sphere	Avg Z Coord Outer Sphere	Avg X Coord Inner Sphere	Avg Y Coord Inner Sphere	Avg Z Coord Inner Sphere	RMS vector (Pixels)	RMS Vector (µmeters)
1	0.612	512.90	432.23	513.75	511.78	432.54	511.88	2.21	1.35
2	0.591	514.25	396.90	511.56	512.32	395.85	513.13	2.69	1.59
3	0.612	514.32	385.29	512.67	511.66	385.96	512.48	2.75	1.68
6	0.612	512.45	380.18	511.26	511.79	379.17	513.32	2.39	1.46
7	0.612	546.68	412.36	549.67	549.30	412.77	550.16	2.70	1.65
8	0.612	512.70	393.25	512.53	511.84	393.14	512.41	0.87	0.53

LoTRT DR Transmission Images are used to validate critical dimensions

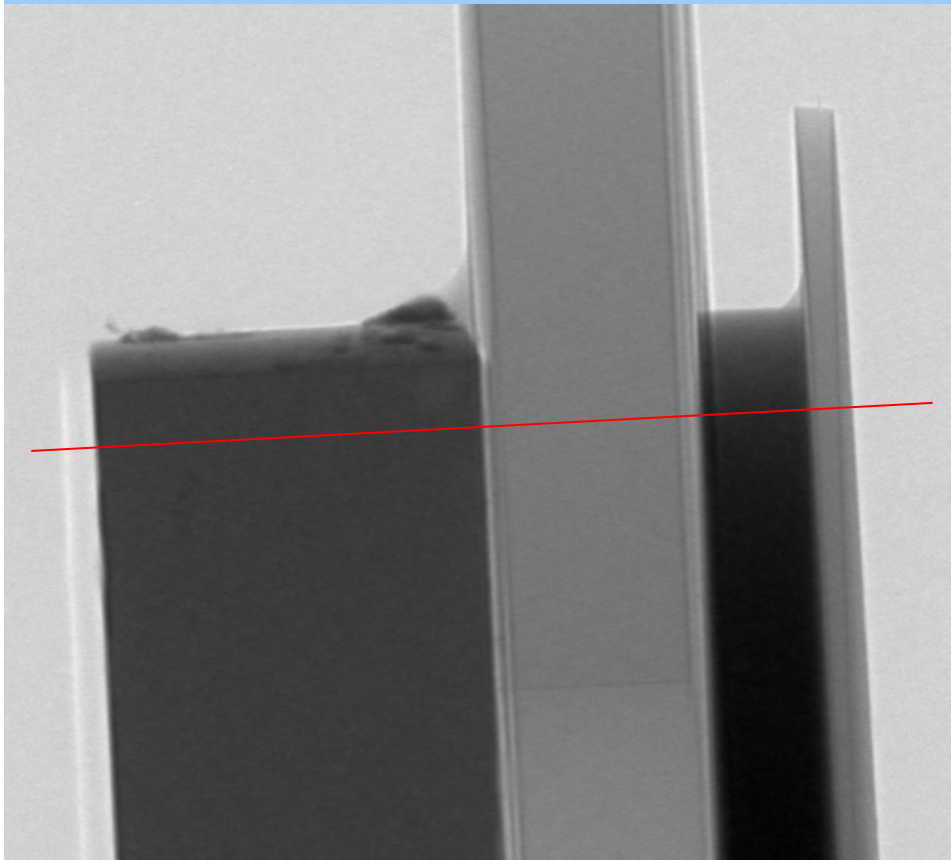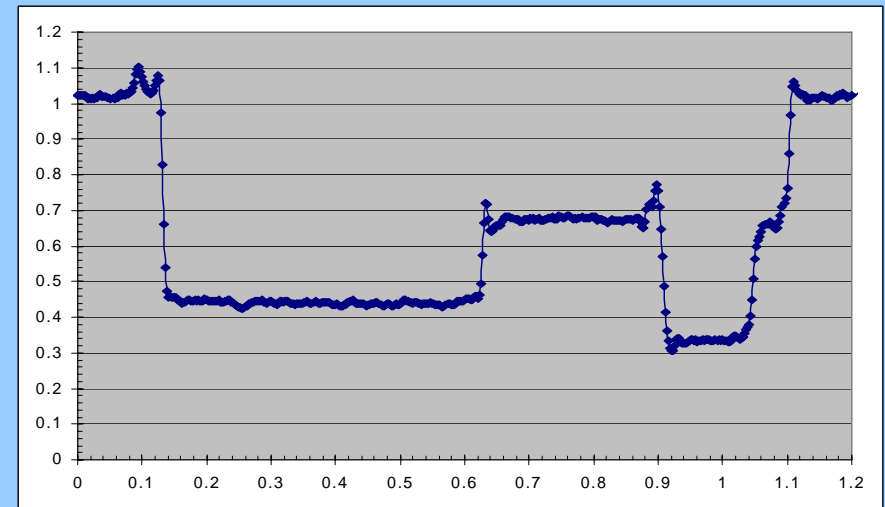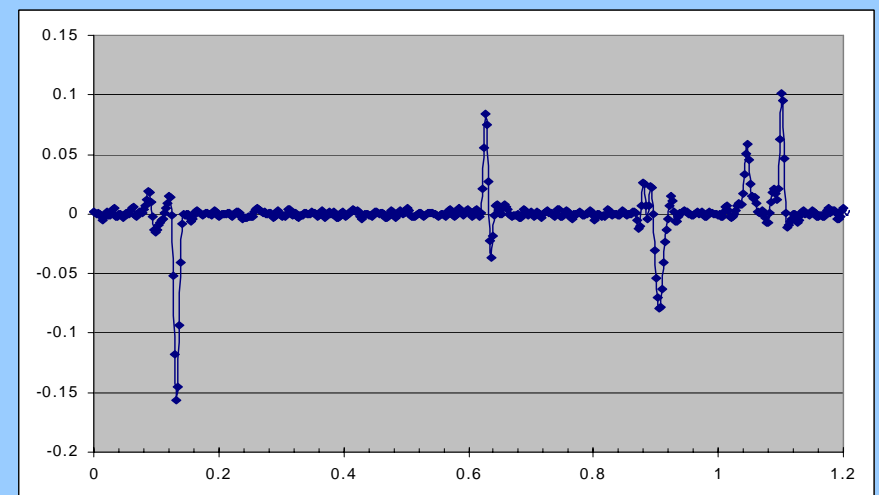**Image cropped and 1X1 binned**

90 kV, 0.067 ma
120 Sec Integration
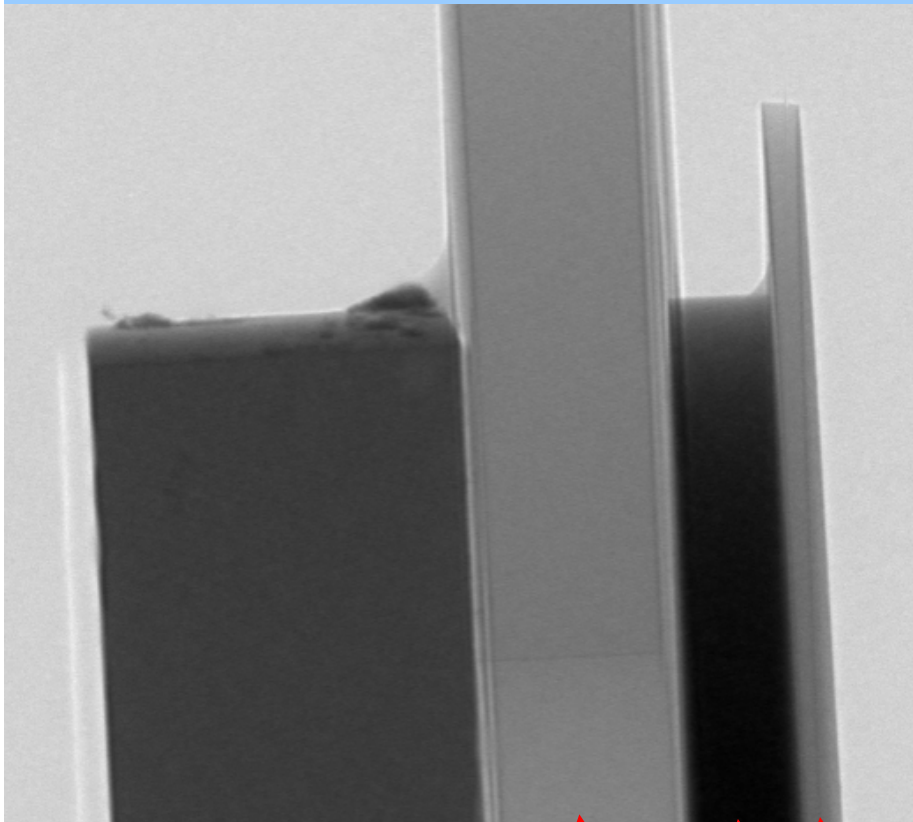5X FOV Setting
1 X 1 Binning, 1 Frame Avg
202 mm SDD, 197 mm SOD

Line-out values

Derivative values

We showed as-built target met specifications or were slightly out of spec

Derivative values

L1   L2   L3   L4
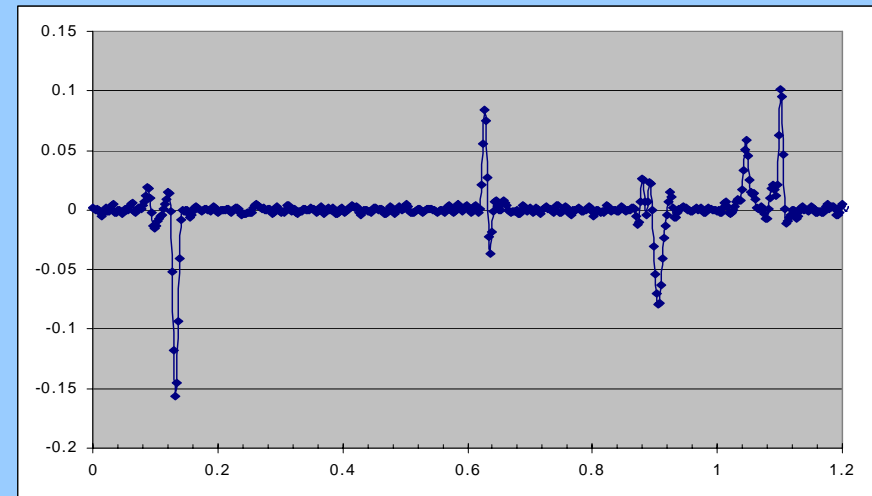
	L1 (mm)	L2 (mm)	L3 (mm)	L4 (mm)
Drawing Values	0.5 ± 0.003	0.3 ± 0.005	0.1 - 0.15* ± 0.005	0.05 ± 0.005
Measured Values	0.496	0.281	0.139	0.053

- Layered values are taken from Deg AAA05-500076AB
- L1 is not indicated on the drawing
- * L4 values vary in size 0.1, 0.125 and 0.15 mm

BrCH/SU8 gradient modeling